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Proceedings of the Diesel Particulate Control/Alternative Fuels Symposium Held at Chicago, Illinois on January 27-28, 1987

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16. ABSTRACT

Two-day symposium on diesel particulate control and alternative fuels including environmental and health issues of diesel emissions, diesel control technology, a survey of alternative fuels (methanol, methane), achieving heavy duty engine emission standards, and government policies: the choices. Symposium format is introductions, welcome, keynote address by Charles Gray of U.S. EPA's Office of Mobile Sources, four panel discussions with participation by diverse groups: air pollution control agency officials, industry, environmental groups and active researchers.

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January 27-28, 1987
Bismarck Hotel
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Sponsored By

U.S. EPA
Region 5, Chicago, Illinois
Motor Vehicle Emissions Laboratory
Ann Arbor, Michigan

Chicago Lung Association,
Chicago, Illinois

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U.S. Environmental Protection Agency
Region 5
Chicago, Illinois

Emission Control Technology Division
Motor Vehicle Emissions Laboratory
Ann Arbor, Michigan

Chicago Lung Association
Chicago, Illinois

Diesel Particulate Control/ Alternative Fuels Symposium

January 27-28, 1987

JANUARY 27, 1987

8 a.m. Registration

9 a.m. Introduction...Steve Rothblatt,
Chief, Air and Radiation Branch, Region 5, U.S.EPA

9·05 a.m. Welcome to U.S. EPA Region 5..........................Frank M. Covington
Deputy Regional Administrator, Region 5,
U.S. Environmental Protection Agency (U.S. EPA)

9:15 a.m. Keynote Address...Charles Gray,
Director, Emission Control Technology Division,
Office of Mobile Sources, U.S.EPA

10:00 a.m Break

10:15 a.m. Environmental and Health Issues (panel discussion)...........moderator,
John Kirkwood,
Chicago Lung Association

Characteristics of Diesel Emissions .... Dennis Schuetzle,
Ford Motor Company

Risk Analysis.................................Dr. Joellen Lewtas,
Chief, Genetic Bioassay Branch, U.S. EPA

Overview of Health Effects Institute Research on
Diesel Particulates...................... Dr. Rashid Shaikh,
Health Effects Institute (HEI)

12 noon Lunch

1:30 p.m. Inhalation Studies...........................Dr. Robert K. Jones,
Lovelace Inhalation Toxicology Research Institute

Health Effects of Methanol.......................Dr. Robert Kavet,
ERI Incoporated,
formerly of HEI

Agenda

Diesel Particulate Control/ Alternative Fuels Symposium

Health Effects Studies at General Motors...Dr. Jaroslav J. Vostal,
General Motors Research Laboratory

Present/Future Standards ....David Doniger,
Natural Resources Defense Council

2:50 p.m. Break

3:00 p.m. Diesel Control Technology (panel discussion)..................moderator,
Sarah LaBelle,
Chicago Transit Authority

Engine Modifications to Meet Future Standards ......Thomas Baines,
Emission Control Technology Division, U.S.EPA

Trap Oxidizers ....Bruce Bertelsen,
Manufacturers of Emission Controls Association

Status of Trap Oxidizer Projects.....................Thomas Baines

Impact of Cleaner Diesel Fuels on Cost ....Timothy Sprik,
Emission Control Technology Division, U.S.EPA

JANUARY 28, 1987

9 a.m. Survey of Alternative Fuels (panel discussion)................moderator,
Dr. Barry Nussbaum,
Chief, Operations and Compliance Policy Branch, U.S.EPA

Methanol: sources, markets, emissions, safety..........Bob Murray,
Director, Worlwide Methyl Fuels,
Celanese Chemical Company

Methane: sources, markets, emissions, safety..Dr. Jeffrey Seisler,
American Gas Association

Operational Aspects of the Canadian Methanol in Large Engine Program ....Tom Timbario,
Sypher-Mueller International

10:30 a.m. Break

Agenda
Diesel Particulate Control/
Alternative Fuels Symposium

10:45 a.m. The Use Of Methanol Fuels To Achieve Heavy Duty Engine Standards..................................moderator,
Thomas Baines,
Emission Control Technology Division, U.S.EPA

Environmental Benefits of Methanol Fueled Heavy Duty Engines..................................Jeff Alson,
Emission Control Technology Division, U.S. EPA

Meeting EPA Emission Standards.....................Charles Napier,
M.A.N.

Methanol Engine Development.........................Don Petersen,
Detroit Diesel Allison - GM

12 noon Lunch

1:30 p.m. Government Policies: The Choices (panel discussion)............moderator
Steve Rothblatt,
Chief, Air and Radiation Branch, Region 5, U.S.EPA

Existing Alternative Fuel Fleets.................Vincent DeMarco,
Urban Mass Transportation Administration (UMTA)

Methanol/Ethanol/Natural Gas.....................Eugene Ecklund,
Department of Energy

Opportunities for Future Demonstration Projects.........Paul Fish,
Region 5, UMTA

3 p.m. Closing Statement.......................................Steve Rothblatt

OPENING REMARKS

DIESEL PARTICULATE CONTROL/ALTERNATIVE FUELS SYMPOSIUM

JANUARY 27, 1987
CHICAGO, ILLINOIS

MR. FRANK M. COVINGTON
DEPUTY REGIONAL ADMINISTRATOR
REGION 5

GOOD MORNING LADIES AND GENTLEMEN. I WOULD LIKE TO EXTEND TO YOU MY PERSONAL WELCOME TO REGION V. I AM GLAD TO SEE SO MANY OF YOU HERE AT THE DIESEL PARTICULATE CONTROL/ALTERNATIVE FUELS SYMPOSIUM WHICH WE ARE SPONSORING ALONG WITH EPA'S MOTOR VEHICLE EMISSIONS LABORATORY AND THE CHICAGO LUNG ASSOCIATION.

IF YOU HAVE HAD THE MISFORTUNE OF BEING CAUGHT BEHIND A BUS, AS IT LEAVES A STOP, OR BEING STOPPED IN RUSH HOUR TRAFFIC ON THE HIGHWAY, SURROUNDED BY 18 WHEELERS, YOU UNDERSTAND THE PUBLIC'S CONCERN OVER DIESEL PARTICULATES.

UNLIKE THE INVISIBLE HYDROCARBON, NITROGEN OXIDES, AND CARBON MONOXIDE EMISSIONS FROM GASOLINE-POWERED VEHICLES, DIESEL EMISSIONS ARE MOST NOTICEABLE. THEIR BLACK SMOKE AND MALODOROUS SMELL BRING UNIVERSAL DISMAY.

YET, UNTIL 1978, THERE WAS LITTLE RESEARCH ON THE HEALTH EFFECTS OF, AND CONSEQUENTLY, LITTLE REGULATION OF, DIESEL PARTICULATES. NONETHELESS, EVIDENCE HAS ACCUMULATED WHICH HAS CONVINCED EPA THAT STEPS NEEDED TO BE TAKEN TO PROTECT THE PUBLIC FROM THIS POLLUTANT.

IN RESPONSE TO THIS CONCERN, EPA HAS ISSUED NEW REGULATIONS FOR CONTROLLING DIESEL EMISSIONS FROM HEAVY-DUTY ENGINES THAT WILL BEGIN TO BE PHASED IN, IN 1988. IT IS OUR UNDERSTANDING THAT THE ENGINE MANUFACTURERS WILL MOST LIKELY BE ABLE TO MEET THE 1988 STANDARDS THROUGH ENGINE MODIFICATIONS.

HOWEVER, THE MORE STRINGENT STANDARDS FOR 1991 BUS ENGINES IS ANOTHER STORY. MOST EXPERTS AGREE THAT THIS STANDARD CANNOT BE MET WITHOUT ADDITIONAL EXHAUST CONTROLS, MOST LIKELY CATALYST-TRAP OXIDIZERS. THIS RAISES MANY QUESTIONS:

- WILL THE ENGINE MANUFACTURERS AND EMISSION CONTROL DESIGNERS BE ABLE TO MEET THE 1991 STANDARDS ON TIME?
- WHAT WILL HAPPEN IF THEY CAN'T?
- WILL THEY BE ABLE TO DESIGN CATALYST TRAP OXIDIZERS THAT WILL WORK?
- WILL THE SULFUR CONTENT OF DIESEL FUEL HAVE TO BE REDUCED?
- WHAT KIND OF COST INCREASES CAN WE EXPECT FROM THIS NEW TECHNOLOGY?

THESE QUESTIONS WILL BE ADDRESSED BY THIS MORNING'S DIESEL CONTROL TECHNOLOGY PANEL.

EPA HAS HAD A LONG STANDING INTEREST IN EMISSION REDUCTIONS THAT MIGHT BE DERIVED BY CONVERTING ENGINES SO THAT THEY CAN USE ALTERNATIVE FUELS. MANY FUELS HAVE BEEN CONSIDERED, SUCH AS METHANOL, ETHANOL AND METHANE, TO NAME A FEW. THE SECOND DAY OF OUR CONFERENCE WILL BE DEVOTED MOSTLY TO THIS TOPIC. THE ALTERNATIVE FUELS AND GOVERNMENT POLICIES PANELS WILL ADDRESS WHICH FUELS COULD CONTRIBUTE MOST TO IMPROVED AIR QUALITY, WHAT THE COSTS MAY BE, THE ROLE INDUSTRY SEES FOR ALTERNATIVE FUELS, AND WHAT GOVERNMENT PROGRAMS EXIST TO ENCOURAGE THE EXPERIMENTAL USE OF THESE FUELS, AND OTHER MEANS OF CONTROL TECHNOLOGY.

REPRESENTATIVES FROM DIVERSE GROUPS ARE PRESENT FOR THIS SYMPOSIUM. SOME OF YOU ARE AIR POLLUTION CONTROL AGENCY OFFICIALS, SOME OF YOU REPRESENT THE INTERESTS OF INDUSTRY. OTHERS OF YOU SEEK TO REPRESENT THE INTERESTS OF THE ENVIRONMENTAL GROUPS, WHILE STILL OTHERS ARE ACTIVELY ENGAGED IN RESEARCH ON HEAVY DUTY ENGINES. WE ALSO HAVE HERE REPRESENTATIVES FROM VARIOUS

GOVERNMENT AND PLANNING AGENCIES WHO, IN ONE WAY OR ANOTHER, ARE CONCERNED WITH THE QUESTION OF ENERGY USE.

LAST BUT NOT LEAST, SOME OF YOU WORK FOR THE TRANSIT COMPANIES. YOU WILL BE FACED WITH SOME HARD DECISIONS IN THE COMING YEARS CONCERNING EMISSION CONTROL DEVICES AND WHICH ENGINES TO PURCHASE. HOPEFULLY, THIS SYMPOSIUM WILL PROVIDE YOU WITH INFORMATION THAT MAY MAKE THESE DECISIONS EASIER.

RESEARCHERS ARE NOW ACTIVELY ENGAGED IN THE STUDY OF THE CHARACTERIZATION AND HEALTH EFFECTS OF DIESEL PARTICULATE. AS IN ANY NEW FIELD, SCIENCE HAS NOT YET ESTABLISHED A UNIVERSALLY HELD TRUTH CONCERNING THE TRUE LEVEL OF DANGER OF THIS POLLUTNT. OUR PANELISTS TODAY WILL SHARE WITH YOU THEIR LATEST FINDINGS, AND AS TO BE EXPECTED, SOME OF THESE MAY CONTRADICTORY. BUT THAT'S O.K., BECAUSE THAT'S WHAT WE IN REGION V BELIEVE OUR ROLE SHOULD BE--TO FACILITATE A SHARED DISCUSSION AND DEBATE IN THE ENVIRONMENTAL COMMUNITY. WE EXPECT THE HEALTH EFFECTS PANEL TO ENGENDER A LIVELY QUESTION AND ANSWER PERIOD.

AS YOU CAN SEE, WE HAVE A FULL AGENDA OVER THE NEXT TWO DAYS. I WANT TO THANK EACH AND EVERY ONE OF YOU FOR ATTENDING WHAT I CONSIDER TO BE AN IMPORTANT REGIONAL SYMPOSIUM. IT IS MY PERSONAL HOPE THAT THIS SYMPOSIUM WILL SERVE AS A FURTHER CALL TO ACTION TO REDUCE DIESEL PARTICULATE POLLUTION.

NOW I WOULD LIKE TO INTRODUCE OUR KEYNOTE SPEAKER, CHARLES GRAY. CHARLES IS THE DIRECTOR OF THE EMISSION CONTROL TECHNOLOGY DIVISION OF THE EPA'S OFFICE OF MOBILE SOURCES. THE EMISSION CONTROL TECHNOLOGY DIVISION IS RESPONSIBLE FOR: 1) THE DEVELOPMENT AND ESTABLISHMENT OF ALL FEDERAL MOTOR VEHICLE EMISSION STANDARDS (FROM MOTORCYCLES TO AIRCRAFT) AND TEST PROCEDURES; 2) EVALUATION AND ASSESSMENT OF NEW EMISSION CONTROL AND ENERGY

CONSERVATION TECHNOLOGY DEVELOPMENTS; 3) CHARACTERIZATION OF POTENTIALLY HAZARDOUS AND CURRENTLY UNREGULATED EMISSIONS FROM NEW TECHNOLOGIES AND ALTERNATIVE FUELS; 4) SURVEILLANCE PROGRAMS TO ESTABLISH IN-USE VEHICLE EMISSIONS AND FUEL ECONOMY PERFORMANCE; AND 5) NATIONAL LEADERSHIP IN THE IMPLEMENTATION OF MOTOR VEHICLE EMISSIONS INSPECTION AND MAINTENANCE PROGRAMS.

MR. GRAY WAS BORN AND RAISED IN ARKANSAS. HE HAS A BACHELOR OF SCIENCE DEGREE IN CHEMICAL ENGINEERING FROM THE UNIVERSITY OF MISSISSIPPI AND A MASTER OF SCIENCE DEGREE FROM THE UNIVERSITY OF MICHIGAN. HE WORKED WITH ESSO EXPLORATION AND PRODUCTION RESEARCH COMPANY ON PROBLEMS ASSOCIATED WITH PETROLEUM EXPLORATION AND PRODUCTION, AND WITH GULF GENERAL ATOMIC IN THE AREAS OF NUCLEAR ENERGY UTILIZATION AND FUEL REPROCESSING. FOR THE PAST SIXTEEN YEARS HE HAS WORKED FOR THE U.S. ENVIRONMENTAL PROTECTION AGENCY PLAYING A MAJOR ROLE IN THE DEVELOPMENT OF REGULATIONS FOR AIR POLLUTION CONTROL FROM MOBILE SOURCES.

MR. GRAY HAS HAD A LONGSTANDING INTEREST IN ALTERNATIVE FUELS, AND IN THE BENEFITS THAT SUCH FUELS COULD PROVIDE WITH RESPECT TO A CLEANER ENVIRONMENT, INCREASED ECONOMIC GROWTH, AND ENHANCED NATIONAL SECURITY. IN THE MID-1970'S HE WAS THE EPA PROGRAM MANAGER FOR ALTERNATIVE TRANSPORTATION FUELS, AND HE CURRENTLY HEADS THE EPA DIVISION WHICH OVERSEES MOST OF THE AGENCY'S ALTERNATIVE FUELS RESEARCH AND ANALYSIS. HE IS CO-AUTHOR OF "MOVING AMERICA TO METHANOL: A PLAN TO REPLACE OIL IMPORTS, REDUCE ACID RAIN, AND REVITALIZE OUR DOMESTIC ECONOMY," A BOOK PUBLISHED BY THE UNIVERSITY OF MICHIGAN PRESS.

WITHOUT FURTHER ADO I GIVE YOU CHARLES GRAY.....

5

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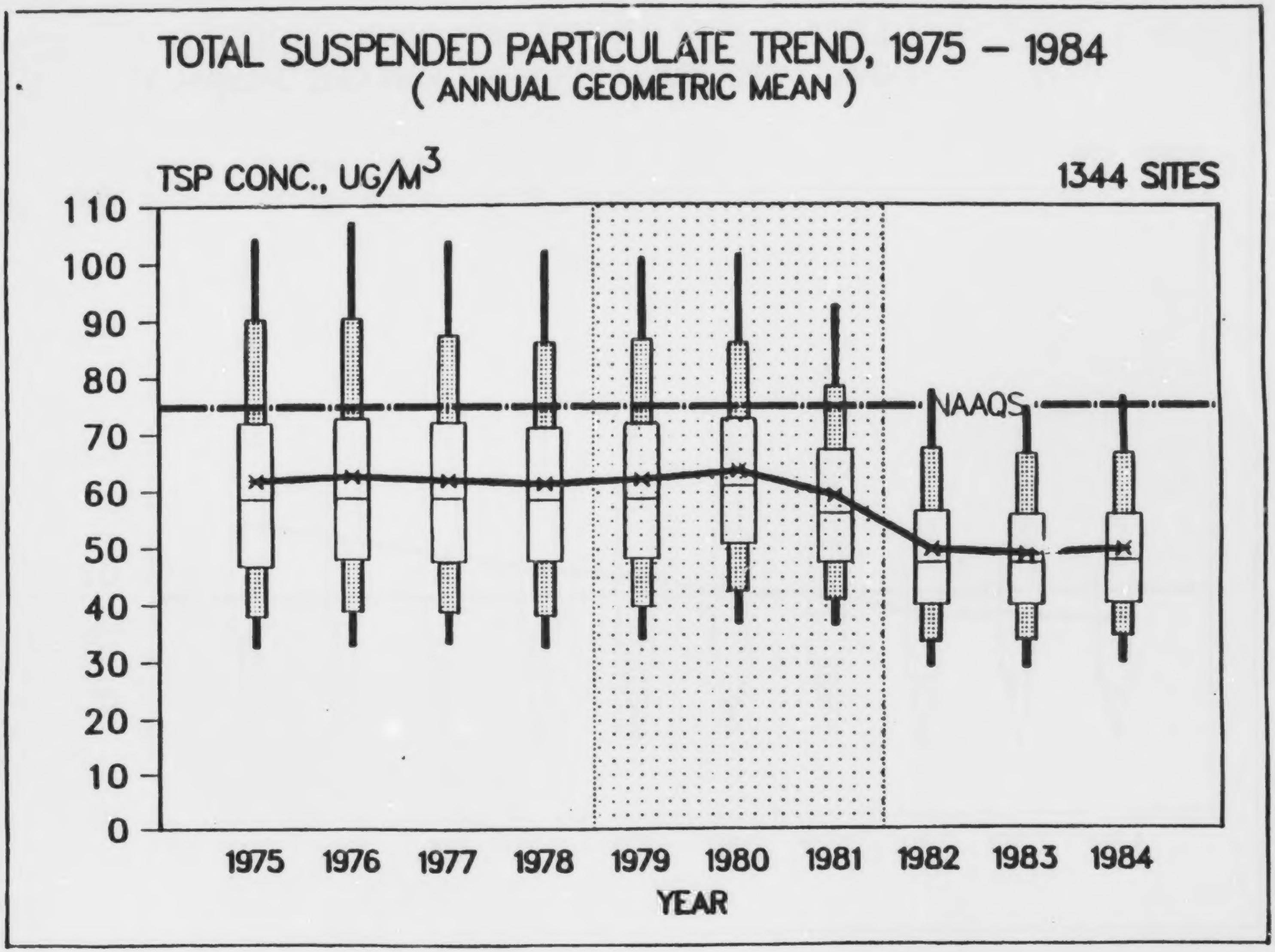
U.S. EPA Region V

The EPA Perspective on the Need for Alternative Vehicle Fuels

Highlights of the Keynote Address for the
EPA Region 5 Diesel Particulate Control/Alternative Fuels Symposium

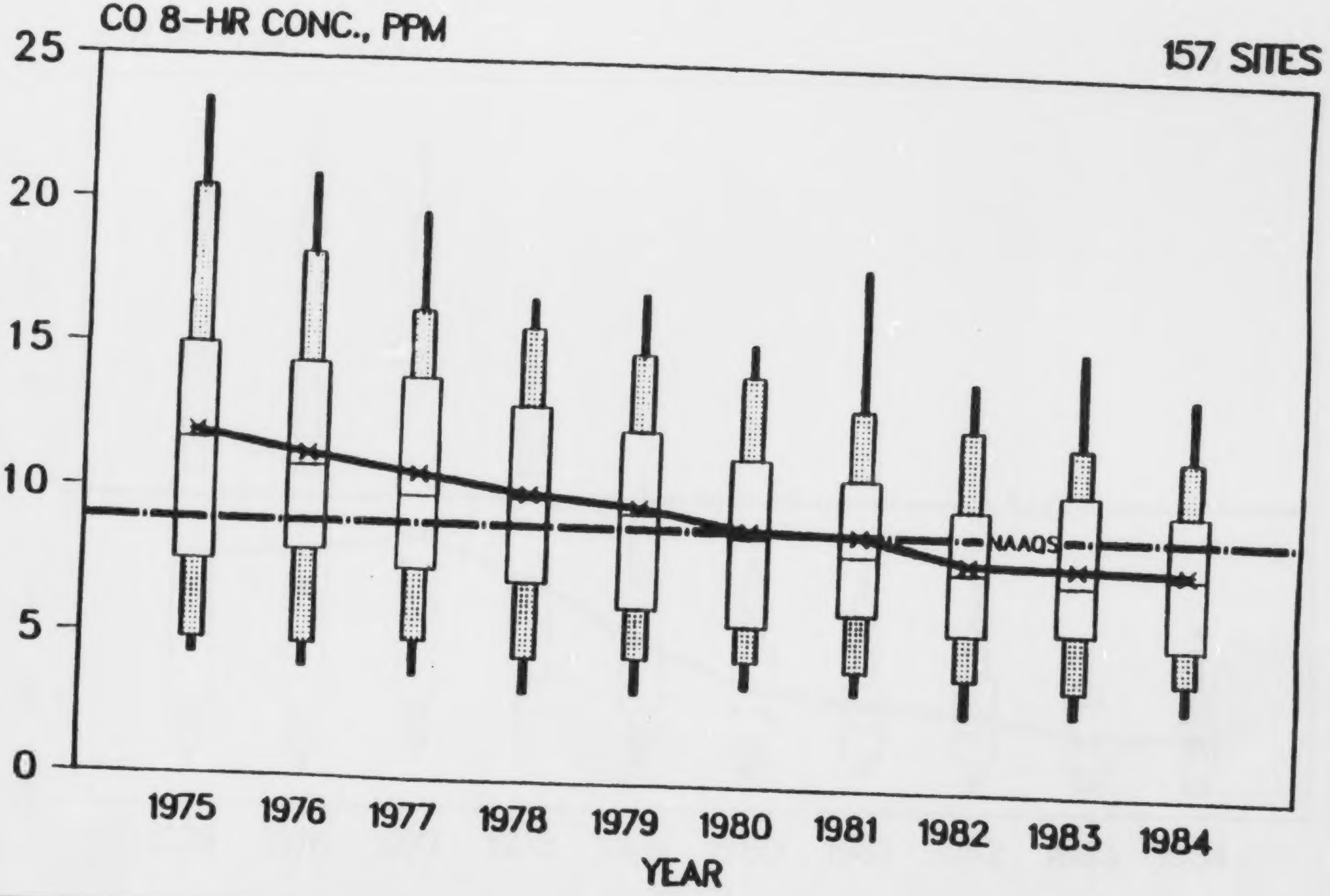
January 27, 1987

Charles L. Gray, Jr.
Director of the Emission Control Technology Division
Office of Mobile Sources
Environmental Protection Agency

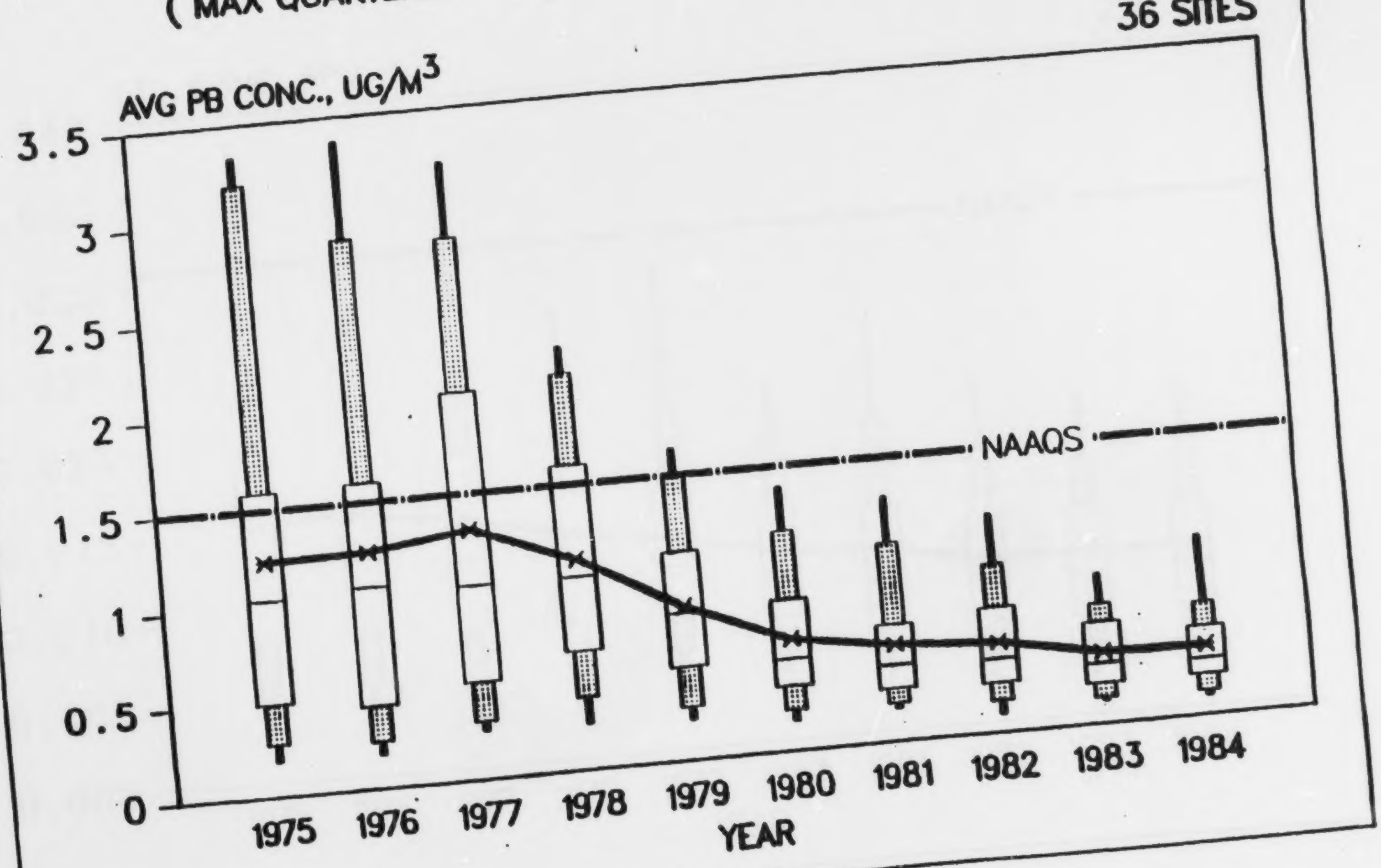


TOTAL SUSPENDED PARTICULATE TREND, 1975 – 1984
(ANNUAL GEOMETRIC MEAN)

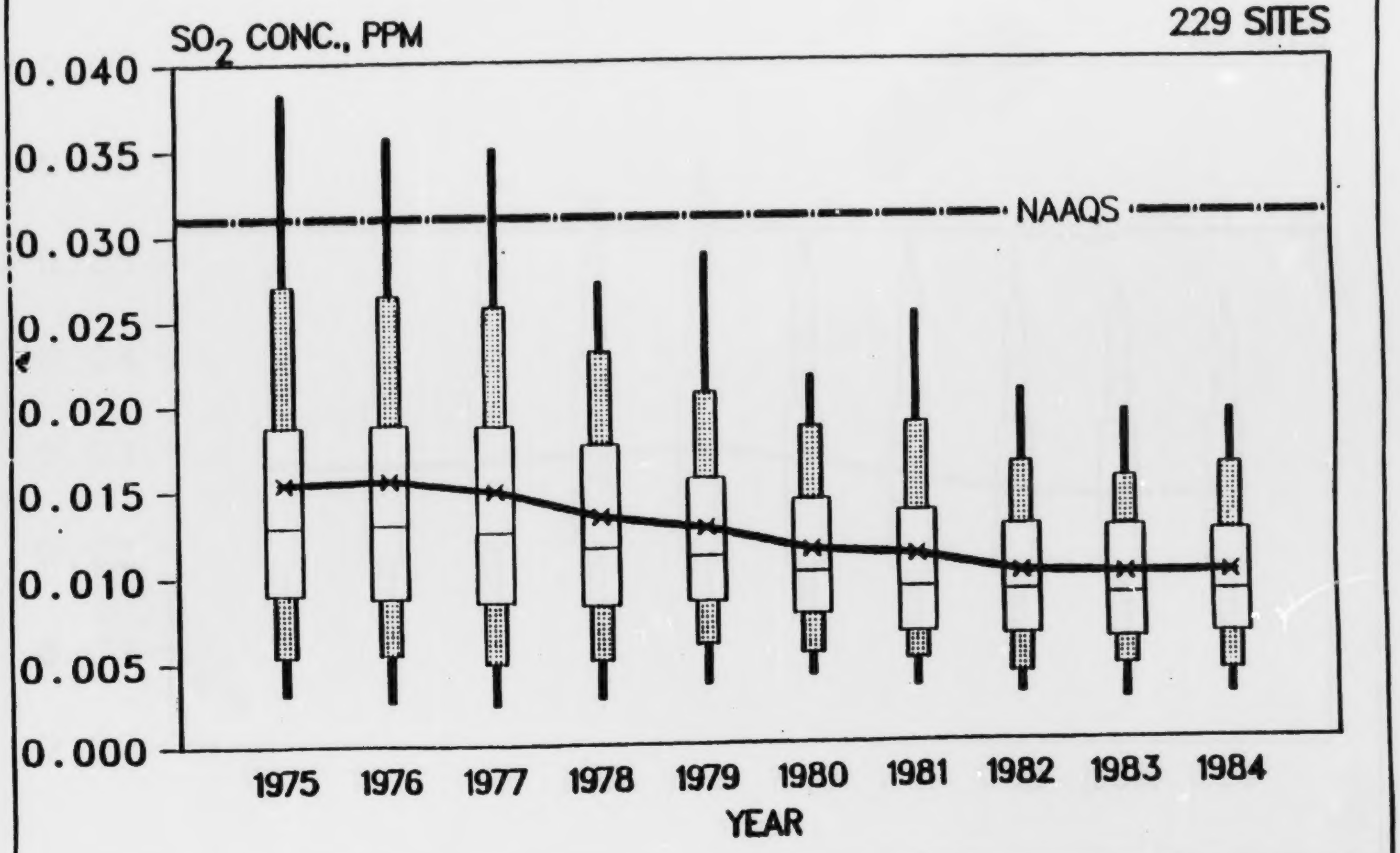
CARBON MONOXIDE TREND, 1975 – 1984
(ANNUAL 2ND MAX 8–HR NONOVERLAPPING AVG)

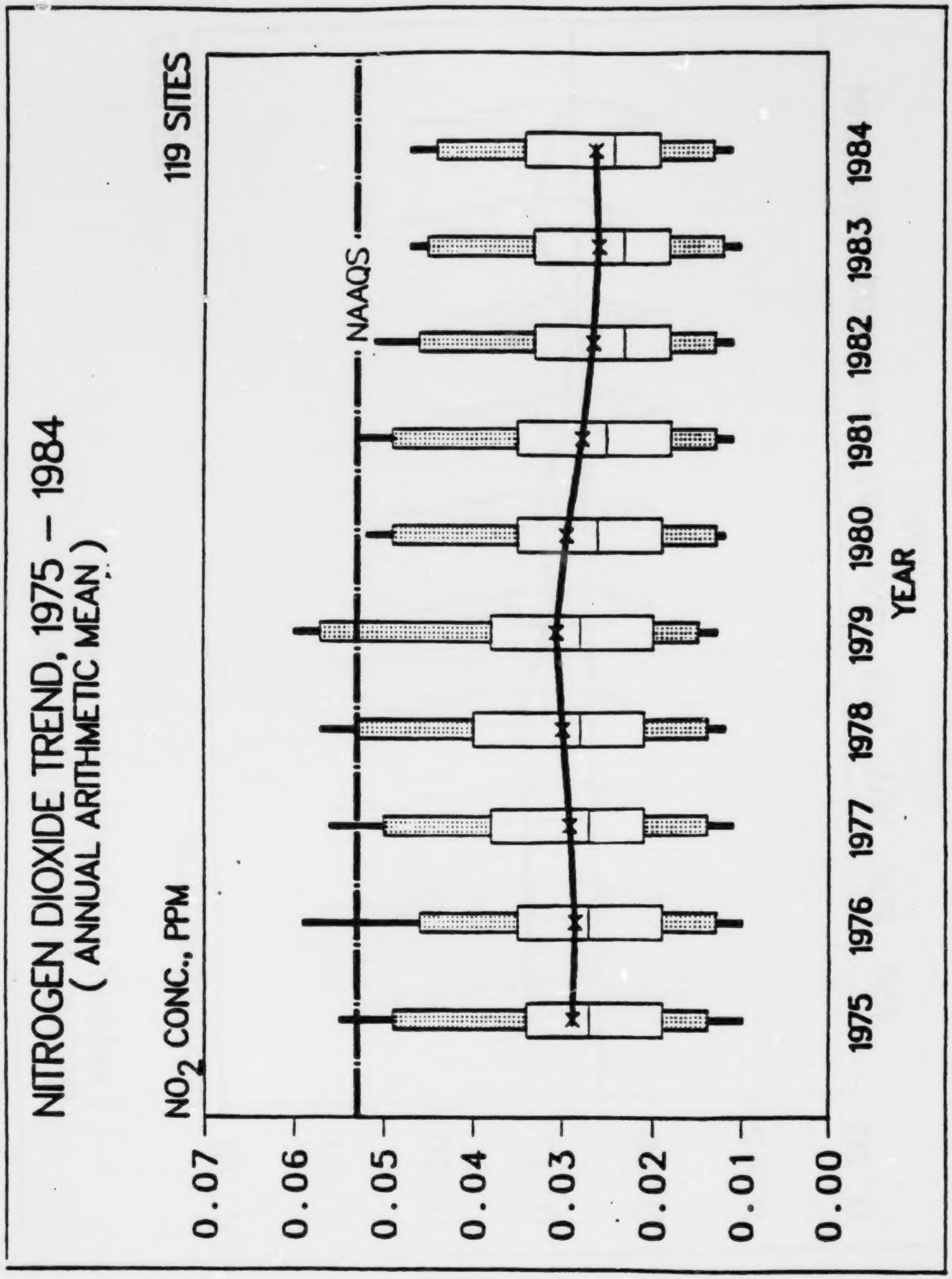


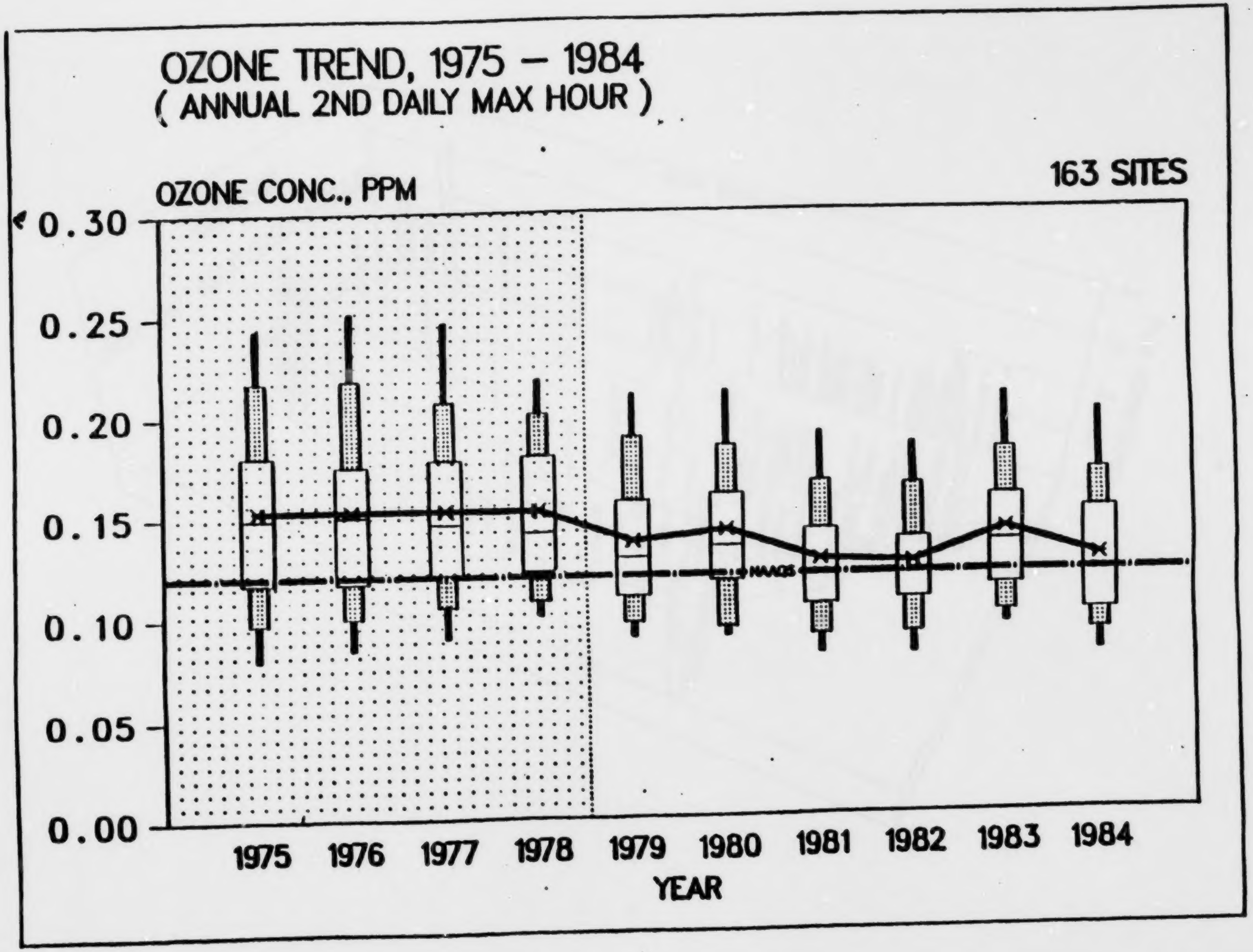
LEAD TREND, 1975 – 1984
(MAX QUARTERLY AVG)



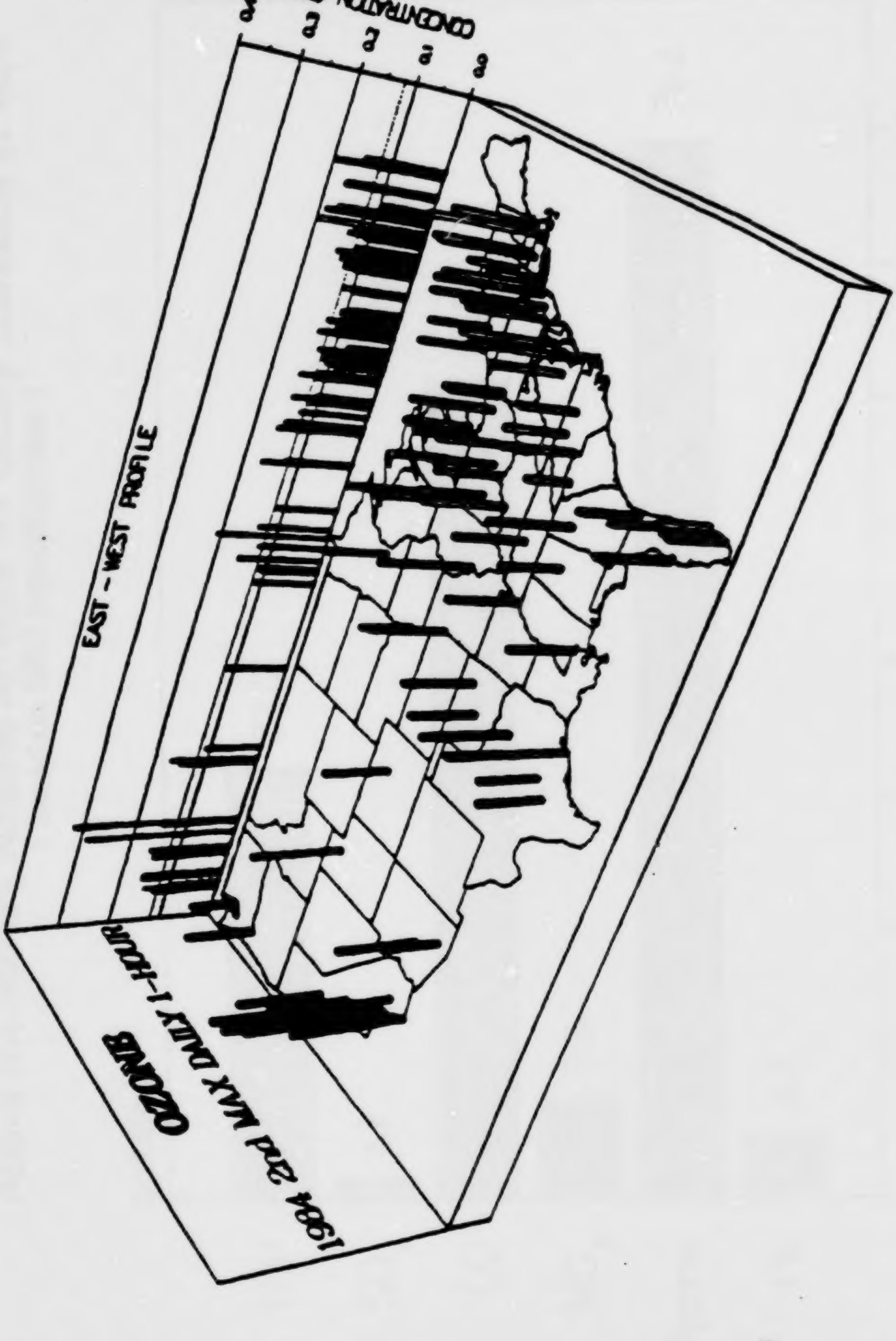
SULFUR DIOXIDE TREND, 1975 – 1984
(ANNUAL ARITHMETIC MEAN)




NITROGEN DIOXIDE TREND, 1975 – 1984
(ANNUAL ARITHMETIC MEAN)
NO_2 CONC., PPM
119 SITES
NAAQS
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
YEAR

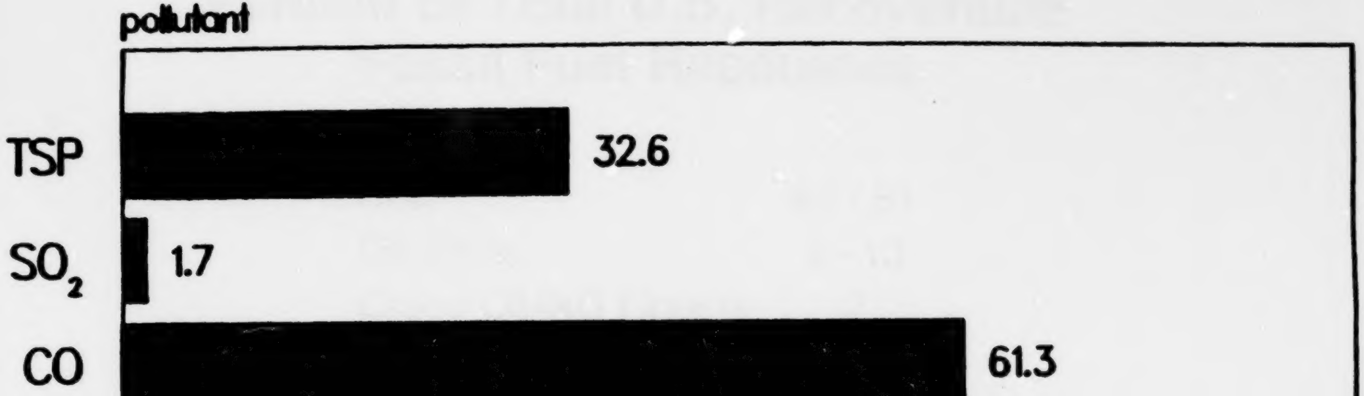


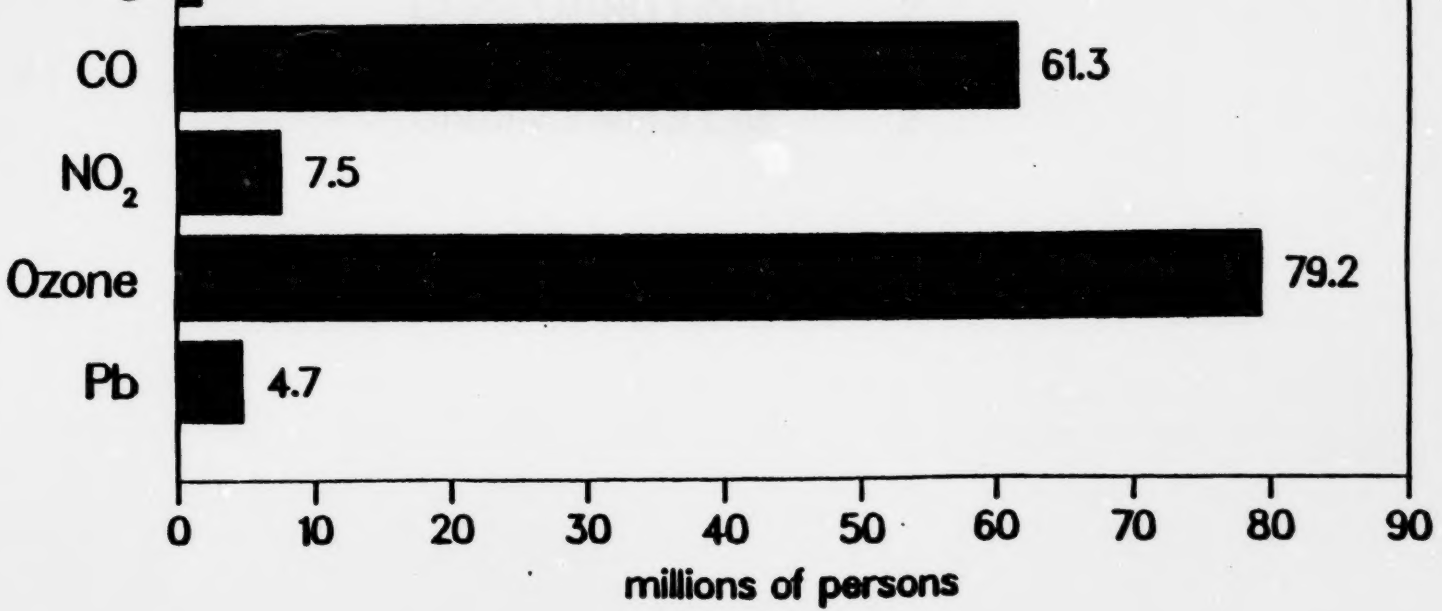
OZONE TREND, 1975 – 1984
(ANNUAL 2ND DAILY MAX HOUR)


OZONE
1984 2nd MAX DAILY 1-HOUR
EAST - WEST PROFILE
CONCENTRATION (PPM)

Number of Persons Living in Counties with Air Quality Levels Above the Primary National Ambient Air Quality Standards in 1984

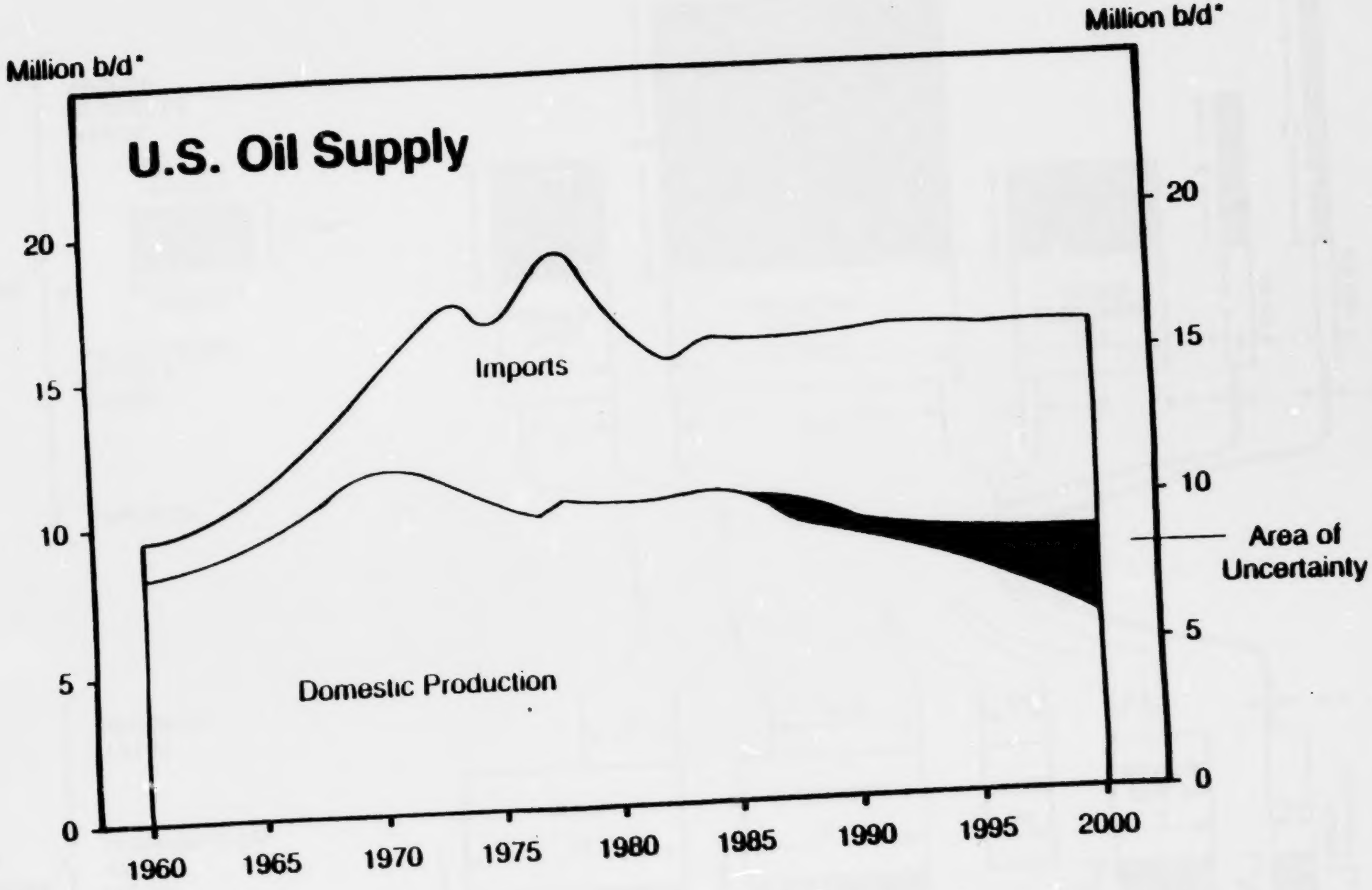
(Based on 1980 population data)




CO
61.3
NO$_2$
7.5
Ozone
79.2
Pb
4.7
0
10
20
30
40
50
60
70
80
90
millions of persons

Percent of Total U.S. Recoverable Fossil Fuel Resources

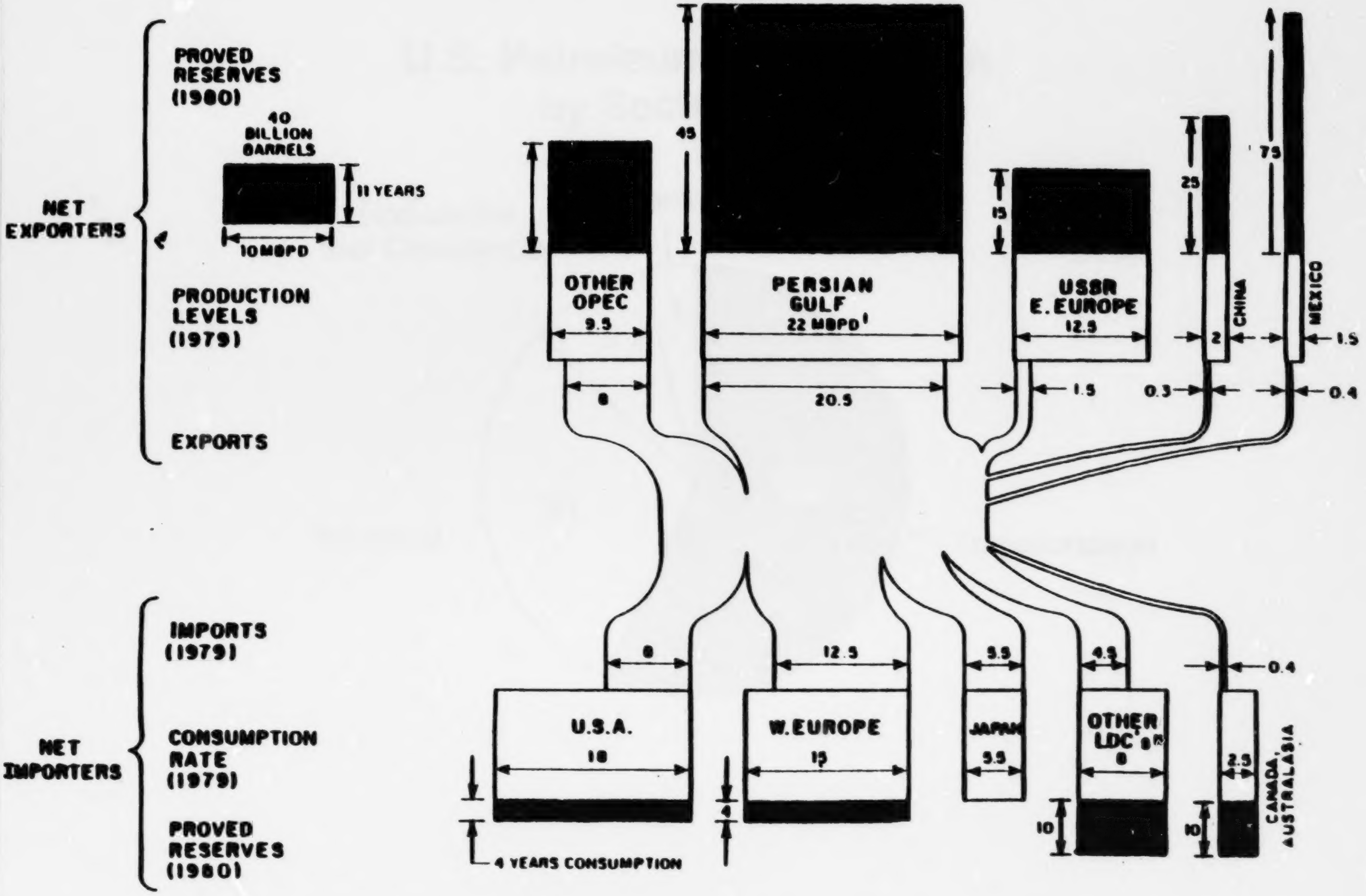
Coal	81 - 91
Oil Shale	3 - 13
Crude Oil/NG Liquids	2
Conventional Gas	2
Unconventional Gas	2



*Million barrels/day

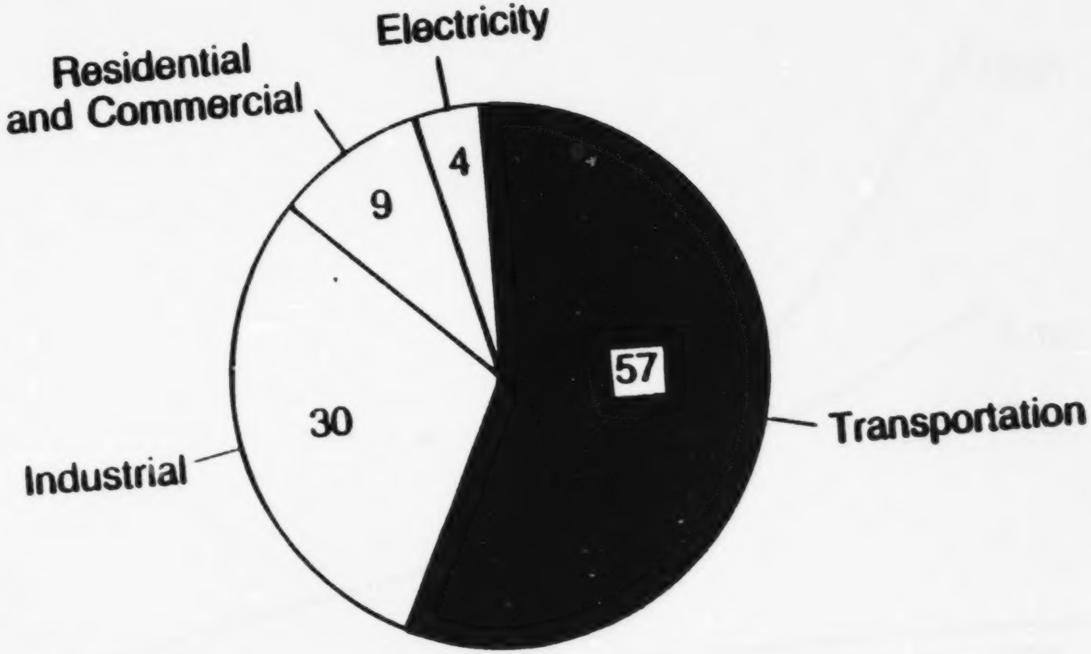
THE WORLD OIL SITUATION IN 1979

TOTAL WORLD PRODUCTION (MBPD[1]) —— 1979(65.7)

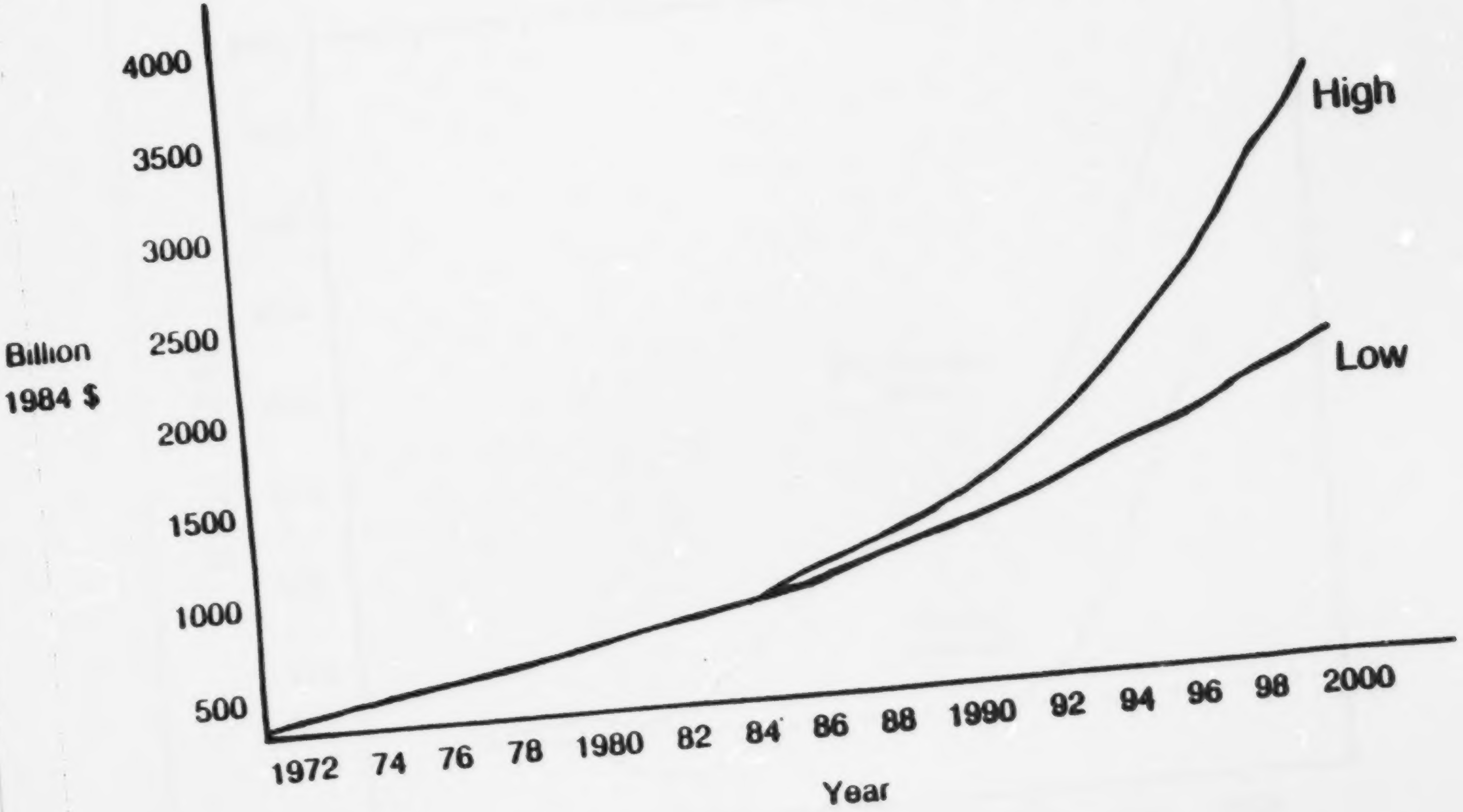

NET EXPORTERS
PROVED RESERVES (1980)
40 BILLION BARRELS
11 YEARS
10 MBPD
PRODUCTION LEVELS (1979)
EXPORTS
OTHER OPEC
9.5
8
PERSIAN GULF
22 MBPD[1]
45
20.5
USSR E. EUROPE
12.5
15
1.5
CHINA
2
25
0.3
MEXICO
1.5
75
0.4
NET IMPORTERS
IMPORTS (1979)
CONSUMPTION RATE (1979)
PROVED RESERVES (1980)
U.S.A.
18
8
4 YEARS CONSUMPTION
W. EUROPE
15
12.5
4
JAPAN
5.5
5.5
OTHER LDC'S[2]
8
4.5
10
CANADA, AUSTRALASIA
2.5
0.4
10

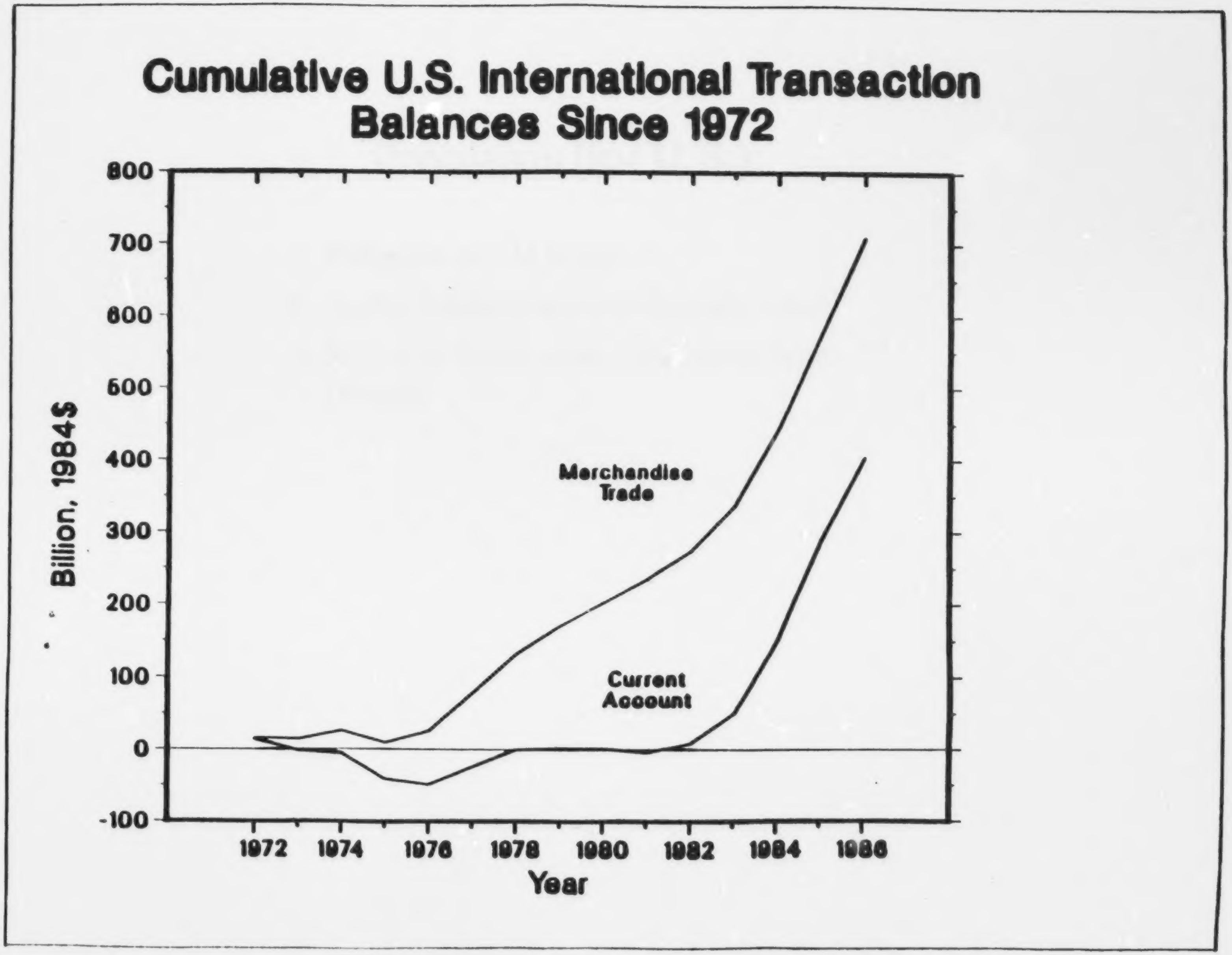
1 1 MBPD = ONE MILLION BARRELS PER DAY

U.S. Petroleum Consumption by Sector, 2000



Projected Cumulative Cost of U.S. Crude Oil Imports




Cumulative U.S. International Transaction
Balances Since 1972
Billion, 1984$
800
700
600
500
400
300
200
100
0
-100
Merchandise
Trade
Current
Account
1972
1974
1976
1978
1980
1982
1984
1986
Year

Problems (for U.S.):

1. Reliance on Oil Imports
2. Sulfur Emissions from Burning Coal
3. NOx and Particulate Emissions from Diesels

Concept

Burn low-sulfur coal in power plants
and convert high-sulfur coal to methanol
for transportation

Methanol from High-Sulfur Coal

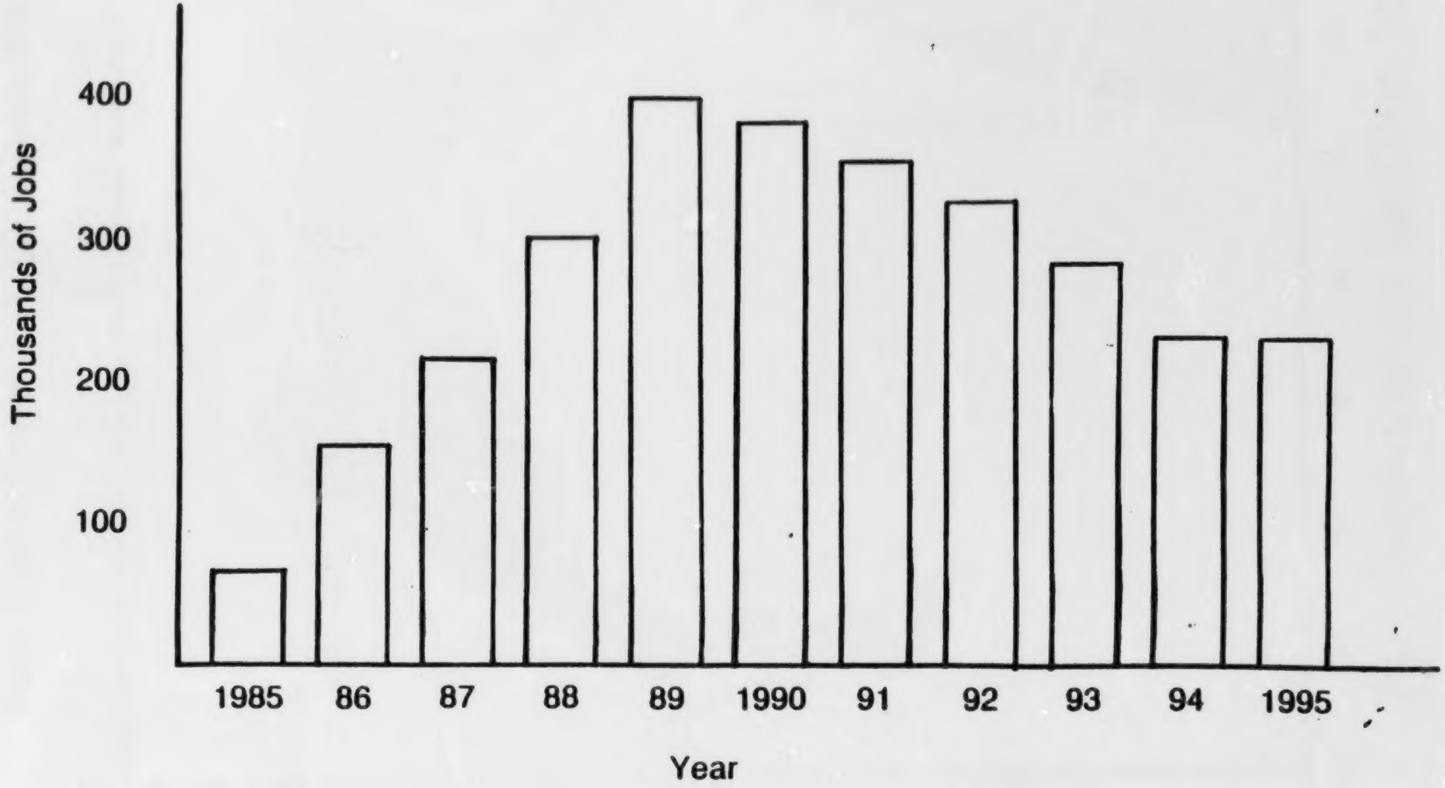
	Coal Shift (10^6 tons)	SO_2 Reduction (10^6 tons)	Number of 100,000 BPD Methanol Plants	Capital Cost of Plants ($ Billion)
Maintain Actual 1981 Market				
1.04% S Coal	189	9*	25 (20%)**	63
0.64% S Coal	351	12	46 (37%)	115
Fulfill Expected 1990 Market				
1.04% S Coal	254	11	34 (27%)	85
0.64% S Coal	416	13	55 (44%)	138

---

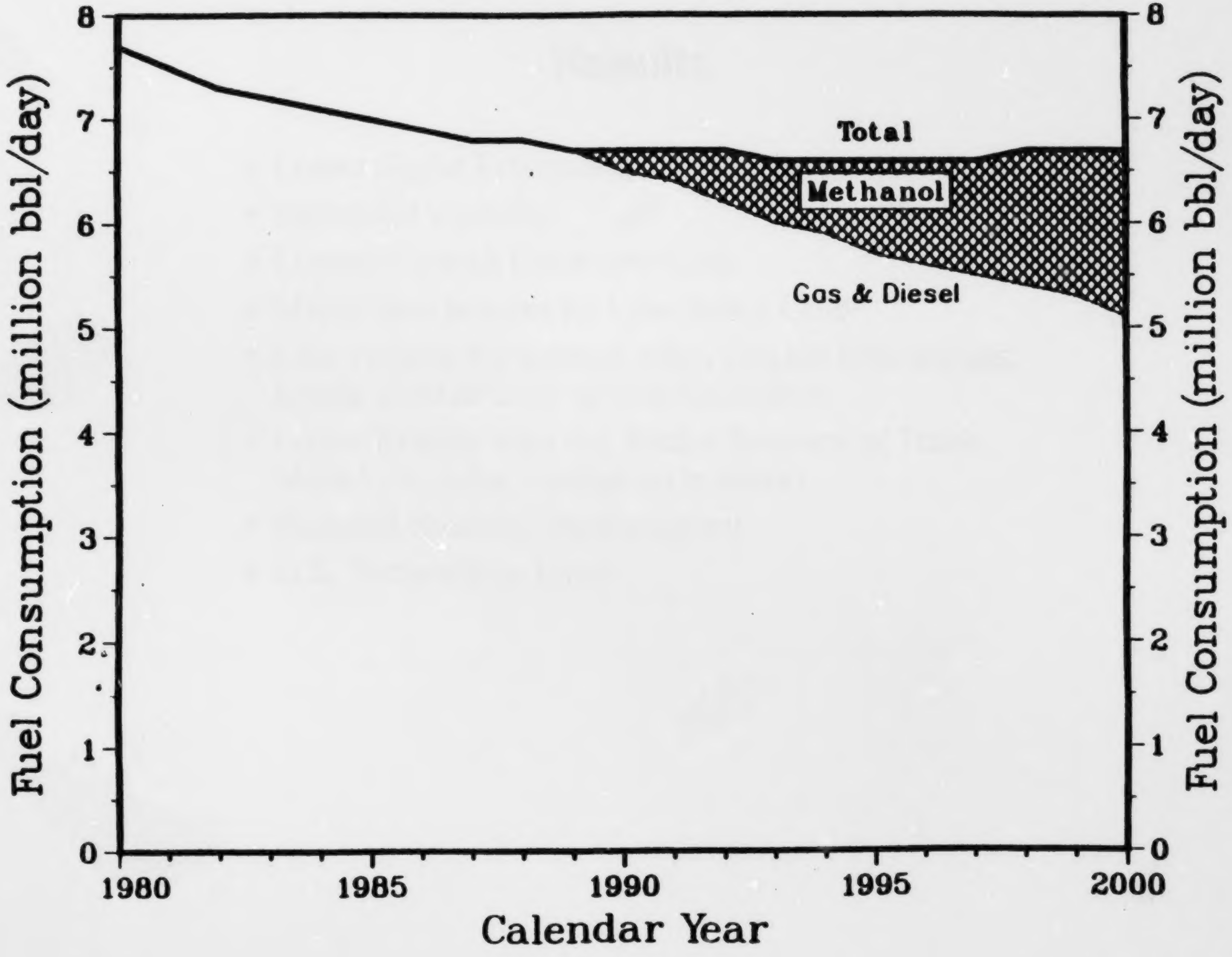
*Corresponds to about 10 to 15 billion dollars in Scrubber Capital Costs. (If invested in methanol plants would reduce methanol cost 10-15%.)

**% of 1990 Motor Fuel Consumption.

Projected Employment of 1.5 MBPD Coal-to-Methanol Industry



Past and Projected Highway Fuel Demand



Results

- Lower Sulfur Emissions
- Improved Visibility
- Lowest Overall Electricity Cost
- Major New Market for Low-Sulfur Coal
- Low Vehicle Emissions, High Engine Efficiencies, Lower Overall Cost of Transportation
- Lower Energy Imports, Better Balance of Trade, More U.S. Jobs, Hedge on Inflation
- National Security Improvement
- U.S. Technology Lead

Methanol is a Superior Alternative Fuel

Producible in massive quantities from domestic feedstocks

Production technology is commercially feasible

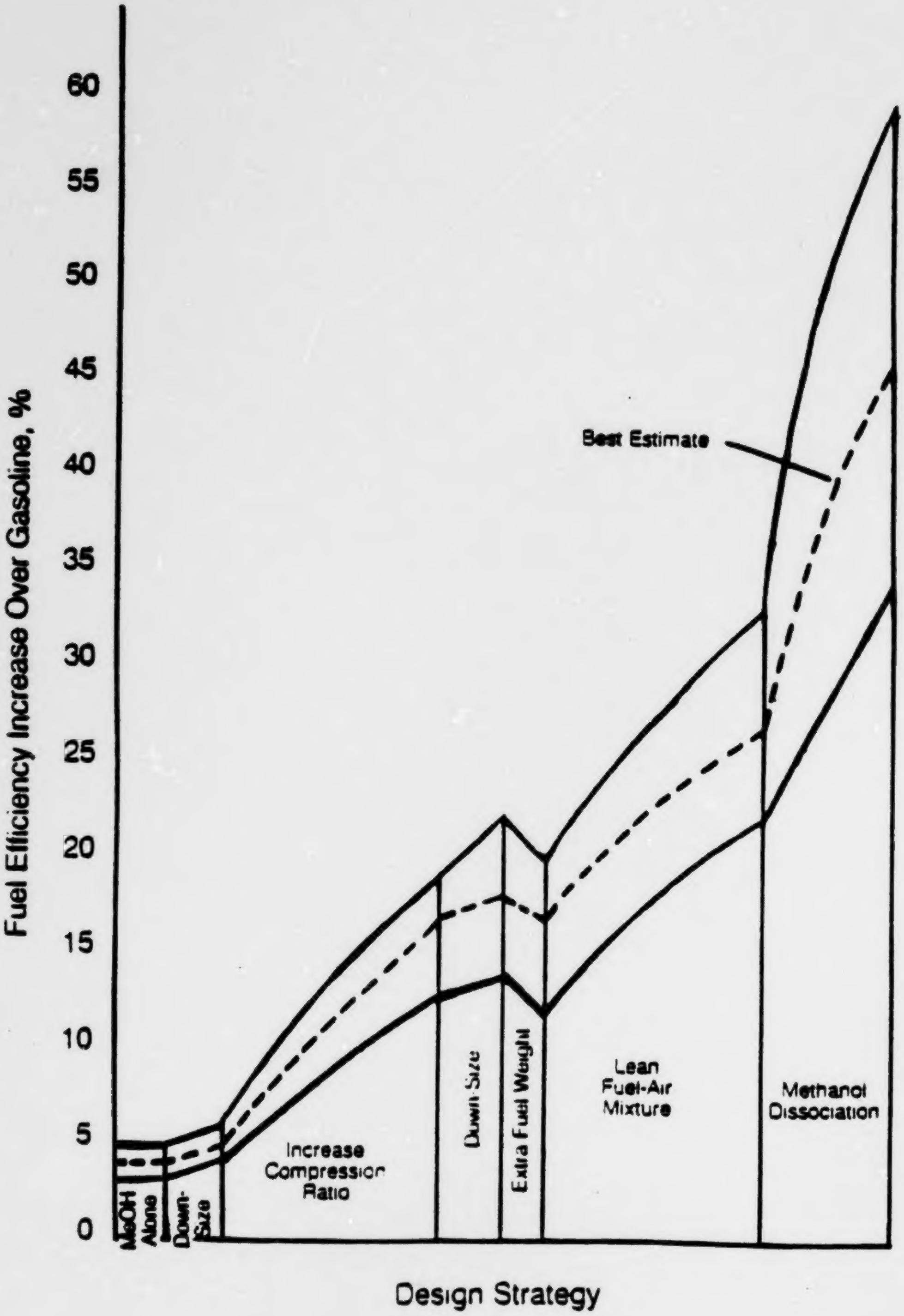
Highly efficient vehicle fuel

Generally compatible with existing vehicle and distribution system designs

More benign environmental impacts

Fuel economics favorable compared to other alternatives

Methanol Engine Efficiency



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Carcinogenic and Mutagenic Effects of Diesel Engine Exhaust
N. Ishinishi, A. Koizumi, R.O. McClellan and W. Stöber eds

FACTORS INFLUENCING THE EMISSION OF VAPOR AND PARTICULATE PHASE COMPONENTS FROM DIESEL ENGINES

DENNIS SCHUETZLE

Ford Motor Co Research Staff, Scientific Research Lab.-S3061,
Box 2053, Dearborn, MI 48121, USA

JAMES A. FRAZIER

National Research Council, National Academy of Sciences,
Washington, D. C. 20418, USA.

INTRODUCTION (1-10)

Vehicle emissions are comprised of thousands of chemical components. However, only a small percentage of these many compounds have potential toxicological significance. The probability for identification of the most biologically active compounds presents an enormous, if not an impossible task. An equally difficult task is to make a quantitative assessment of the human health risks associated with exposure to these chemicals.

Considerable progress has been made during the past several years in the identification of several chemicals with significant mutagenic activity in diesel exhaust. Approximately 40% of the total mutagenicity (TA98 strain) of diesel particulate extracts can be accounted for by several nitrated polynuclear aromatic hydrocarbons (nitro-PAH). Much of this progress has come about by the use of an analytical tool called "bioassay directed chemical analysis" which is a combination of short-term bioassays and chemical analysis (1). Some of the mutagenic nitro-PAH have also been found to be carcinogenic in animal tests as reported by others in this volume.

In 1983 the U.S. National Academy of Sciences (NAS) initiated a study on the "Feasibility of Assessment of Health Risks from Vapor-Phase Organic Chemicals in Gasoline and Diesel Exhaust" (2). In that study several organic chemicals, identified in the vapor phase, were selected as based upon the availability of toxicological and epidemiological information. This information was used in making quantitative and qualitative assessments of the human health risk associated with exposure to each chemical. The purpose of this paper is to summarize the results of the NAS study and extend it to include recent emissions data on chemicals in the gas-phase and particulate-phase as given in Table 1.

SELECTION OF CANDIDATE COMPOUNDS

Table 1 lists the candidate compounds chosen for this study. The choice of these compounds was based upon 1). how representative these candidate compounds are for other components emitted in vehicle exhaust, 2). the availability of emission rate data as a function of operating conditions and aromaticity of the fuel, 3). the availability of emission rate data for light-duty diesel, heavy-duty diesel, and gasoline engines from various manufacturers, 4). the reliability of the emissions data as determined by the analytical protocol (e.g. minimization of artifact formation), 5). the availability of data to determine compound distribution between the particle and gas phases after atmospheric dispersion, 6). the potential to undergo atmospheric reactions to form reaction products of toxicological significance, 7). the reliability of models to determine exposure levels, 8). the availability of relevant toxicological data, and 9). the availability of biomarker (e.g. measurement of chemical adducts in blood) to determine actual levels of exposure.

Table 1 lists the sixteen compounds chosen as candidates for risk assessment studies as based upon these nine criteria. Some of the compounds listed in this table were chosen because they represent a particular class of compounds. For example, a number of quinone derivatives of PAH have been identified in vehicle and ambient air particulates (3,4). The relative proportion of each quinone is dependent on the degree of oxidation, reactivity, and abundance of each PAH species. Since 9,10-anthracenequinone is one of the most abundant PAH-quinones, we chose it as a representative compound. There are possibly hundreds of nitrated-PAH derivatives in vehicle exhaust; 1-nitropyrene being one of the most abundant species (5). The dinitropyrenes (1,3; 1,6; 1,8) are formed from further nitration of the 1-nitropyrene and are present at approximately 1% of the 1-nitropyrene concentration. Therefore we have used 1-nitropyrene to be representative of the dinitropyrenes and other nitro-PAH. Similar arguments can be made for the other species.

TABLE 1

CHEMICALS CHOSEN AS CANDIDATES FOR RISK ASSESSMENT STUDIES

Gas-Phase	Gas and Particle Phases	Particle Phase
CO	anthracene	benzo(a)pyrene
NO_x	pyrene	benzo(e)pyrene
formaldehyde	fluoranthene	9,10-anthracenequinone
propylene	2-nitrofluorene	9-fluorenone
benzene		1-nitropyrene
toluene		2-nitropyrene

FACTORS THAT INFLUENCE EMISSIONS

The emission rates of the candidate compounds from exhaust are dependent upon a large number of factors including engine type, operating conditions and fuels. The purpose of this section is to critically review several studies on this subject including a recent Coordinating Research Council study (6) undertaken at Southwest Research Institute. This study examined the influence of several factors on the emission of four of the candidate compounds, pyrene, benzo(a)pyrene, benzo(e)pyrene and 1-nitropyrene as well as total sample mutagenicity for diesel exhaust. Particulate samples were collected from four different vehicles using a variety of fuels and operating conditions. The following analyses were made on the data generated from that study.

The results of eight tests on the effect of engine type and make on PAH are given in Table 2. The emission rates of the four compounds mentioned above varied by a factor of three. The mutagenicity of the total exhaust particulate extract material varied from 0.8 to 1.3 x 10^{+6} rev./mile for TA98 strain without activation (-S9) and 0.5 to 0.7 x 10^{+6} rev/mile for TA98 strain with activation (+S9). These results are comparable to those reported previously for several of light-duty diesel vehicles (1.0 x 10^{+6} rev./mile (-S9) and 0.4 x 10^{+6} (+S9)) (7).

TABLE 2

EFFECT OF ENGINE TYPE AND MAKE ON EMISSIONS*

Emissions Rate	Vehicle Type			
	Oldsmobile	Mercedes	Volkswagen	Peugot
Pyrene(µg/mi)	39 +- 16	62 +- 15	29 +- 15	24 +- 11
BaP(µg/mi)	1.3 +- 0.9	1.9 +- 0.1	1.6 +- 0.2	0.6 +- 0.1
BeP(µg/mi)	2.3 +- 1.2	5.1 +- 0.2	3.0 +- 0.4	1.3 +- 0.4
1-NP(µg/mi)	3.0 +- 1.0	7.8 +- 2.2	1.8 +- 0.9	3.8 +- 1.4
Mutagenicity (rev./mi/10^{+6})				
TA98(-S9)	1.0 +- 0.4	1.3 +- 0.3	0.8 +- 0.3	0.8 +- 0.2
TA98(+S9)	0.5 +- 0.2	0.7 +- 0.2	0.6 +- 0.2	0.5 +- 0.1

*Duplicate tests for each vehicle run on four different fuels at 22% aromatic composition.

Table 3 shows that the emission of PAH and total mutagenic species are increased by a factor of 3-4 when the fuel aromaticity (e.g. benzene, toluene content) is increased from 22% to 55%. These results are consistent with those of Gross (8), Candelli (9), and Hare (10) for studies of fuel aromatic content on BaP in gasoline engine emissions.

The 22% and 55% aromatic fuels contained 2-24 and 2-60 mg/l of pyrene, respectively. The amount of pyrene in the particulate emissions was not related to the fuel pyrene content, which shows the primary source is formation in combustion and not the amount present in unburned fuel in the exhaust.

Fuel aromaticity has no effect on the emission of 1-nitropyrene (1-NP). These data indicate that some NO_x species such as HNO_3 and not pyrene is the limiting factor in the chemical formation of 1-NP. Further work will be needed to determine if the emission of other nitro-PAH species follows the trend of the 1-nitropyrene.

TABLE 3

EFFECT OF FUEL AROMATICITY ON EMISSIONS AND MUTAGENICITY*

Emission Rate	Fuel Aromaticity	
	22%**	55%**
Pyrene (µg/mi)	39 +- 18	125 +- 39
Benzo(a)pyrene (µg/mi)	1.3 +- 0.5	7.1 +- 3.6
Benzo(e)pyrene (µg/mi)	3.0 +- 1.1	10.3 +- 4.1
1-Nitropyrene (µg/mi)	4.1 +- 1.9	3.7 +- 1.6
Mutagenicity (rev/mi/10^{+6})		
TA98 (-S9)	0.99 +- 0.35	2.9 +- 0.80
TA98 (+S9)	0.61 +- 0.18	2.1 +- 0.49

*Duplicate tests for four vehicles run on standard timing.
**Four different fuels were used for each group of tests.

Table 4 presents data which demonstrate the effect of engine operating conditions on emissions. Changes in engine timing have little effect on the PAH emissions but both the 1-nitropyrene and mutagenicity increase by several times. These increases correlate directly with the increase in NO_x emissions.

In our laboratory we have found that engine load has the most significant effect on the emission of PAH and PAH derivatives. An increase of engine load results in reduction of PAH and mononitro-PAH relative to the partially oxidized PAH derivatives (11).

TABLE 4

EFFECT OF ENGINE OPERATING CONDITIONS ON EMISSIONS*

Emission Rate	Engine Conditions		
	Ret. Timing	Std. Timing	Adv. Timing
Pyrene (µg/mi)	31 +- 20	39 +- 18	35 +- 22
Benzo(a)pyrene (µg/mi)	1.7 +- 1.1	1.3 +- 0.5	1.5 +- 0.6
Benzo(e)pyrene (µg/mi)	3.6 +- 2.1	3.0 +- 1.1	4.2 +- 0.5
1-Nitropyrene (µg/mi)	2.3 +- 0.5	4.1 +- 1.9	15.5 +- 7.7
NO_x (g/mi)	0.9 +- 0.02	1.0 +- 0.01	1.3 +- 0.10
Mutagenicity (rev/mi/10^{+6})			
TA98 (-S9)	2.2 +- 1.6	3.4 +- 1.5	6.4 +- 2.7
TA98 (+S9)	1.0 +- 0.5	1.8 +- 0.7	2.5 +- 1.1

*Duplicate tests for two different vehicles

Emissions data were compiled to determine if the ratios of PAH concentrations could be used to distinguish diesel emissions from other sources of vehicle emissions. The only emissions data compiled was from 1979 and later model vehicles, where samples were collected after dilution. Table 5 summarizes data on the concentration ratios for four of the candidate compounds. Fluoranthene and pyrene are produced in nearly the same quantities, irrespective of engine type and make, engine timing, and fuel. These results indicate that chemical formation and degradation of these two species are similar. Approximately twice as much BeP is emitted as BaP for LDD, HDD and LDG-catalyzed vehicles, irrespective of engine timing and fuel. However, BeP and BaP are emitted in nearly equal quantities for non-catalyzed engines (1.3) which is comparable to BeP/BaP ratios for roadway soil and tunnel particulates.

The ratio of pyrene/BaP is approximately ten times greater for diesel engines than it is for gasoline engines. This ratio may be used to fingerprint the fractional contribution of gasoline to diesel particulate matter in ambient air. The ratio of pyrene/1-nitropyrene is dependent upon the engine type varying from 10 for light-duty diesels to 56 for gasoline engines with catalysts and 102 for gasoline engines without catalysts.

PAH ratios are compiled also for particulates collected from vehicle tunnels and roadway soil. The average ratio of pyrene/BaP (1.5) was similar to that of vehicle particulates collected from gasoline engines (without catalyst). The contribution of diesel emissions to the roadway or tunnel samples using these limited results appears to be minimal.

We have found that the compounds 9,10 anthracenequinone and 9-fluorenone are two of the most abundant PAH derivatives in vehicle exhaust and ambient air particulates. The concentrations of these compounds are dependent upon engine operating conditions. We recommend that routine monitoring of these two compounds be undertaken to establish their concentration and source in ambient air samples.

TABLE 5

RATIOS OF PAH IN PARTICULATES OBTAINED FROM A NUMBER OF VEHICLE SOURCES

Sample Source	FLU/PYR	PYR/BAP	BEP/BAP	PYR/1-NP
Light Duty Diesels (LDD)				
Table 3, this report	-	30	2.1	10
Reference 7	0.8	44	-	12
Reference 12	1.3	42	4.3	-
Reference 13	1.3	24	3.0	-
Reference 14	-	30	-	8
Reference 14	1.3	20	2.2	-
Reference 15	1.0	21	1.1	-
Average	1.1	30	2.5	10
Heavy Duty Diesels (HDD)				
Reference 16	0.7	12	1.6	22
Reference 16	0.8	34	2.0	22
Average	0.8	23	1.8	22
Light Duty Gasoline (LDG)				
Reference 14	-	2.5	-	-
Reference 17	0.9	1.6	1.1	110
Reference 18	1.4	11.7*	1.5	-
Reference 19	-	1.3	-	95
Average	1.1	1.8	1.3	102

TABLE 5 (continued)

Sample Source	FLU/PYR	PYR/BAP	BEP/BAP	PYR/1-NP
Light Duty Gasoline (LDG)-catalyst				
Reference 16	2.9*	2.0	3.0	-
Reference 17	1.2	1.6	1.8	62
Reference 19	-	3.3	-	50
Reference 20	1.0	2.0	2.0	-
Average	1.1	2.2	2.3	56
Tunnel and Roadway Samples				
Roadway soil (Toronto)(21)	1.1	1.4	1.0	-
Roadway soil (England)(21)	1.0	1.9	1.0	-
Baltimore Harbor Tunnel (21)	0.8	1.7	1.0	-
Caldecott Vehicle Tunnel(21)	1.4	0.8	0.7	-
Average	1.1	1.5	1.0	-

*values not used in average

COLLECTION OF A REPRESENTATIVE SAMPLE

Since the discovery of nitrated-PAH in vehicle emissions, research has been undertaken to determine if these compounds are formed in exhaust or as a result of the combustion process.

A number of studies (22,23) have been undertaken in our laboratory and others that demonstrate conversion of particulate phase components can occur during sampling. Several investigators have shown that some loss of PAH occurs during sampling resulting in the formation of PAH derivatives. However, this phenomena can be controlled by adequate air dilution (~10/1) and short sampling times (1 Federal Test Procedure (FTP) cycle). Bradow (24) found that the concentration of 1-nitropyrene was not affected when particulates from a light-duty diesel engine were sampled through a denuder which reduced NO_2 and HNO_3 by 80%. These findings have been confirmed by the work of Lies and Klingenberg as described in this volume.

The ratio of pyrene/BaP and BeP/BaP increases by at least 30 times when 7 ppm NO_2 is added during dilution tube sampling of light-duty diesel exhaust (13) (Table 6). An important consideration is the amount of HNO_3 present in the NO_2 as an impurity. These data confirm that BaP is much more reactive than either pyrene or BeP and that these ratios can be used as an indicator of whether or not chemical reactions have occurred. Several other studies have shown that BaP is more reactive that BeP or pyrene (25).

TABLE 6

RATIOS OF PAH IN VEHICLE PARTICULATES AS A FUNCTION OF SAMPLING TIMES AND CHEMICAL CONVERSION

Sample Source (ref.)	FLU/PYR	PYR/BAP	BEP/BAP	PYR/1-NP
Vehicle Particulates (aged or reacted)				
HDD (26) (SRM1650)	1.2	39	4.8	14
LDD (13)	1.3	20	2.2	-
LDD + 7 ppm NO_2 (13)	1.6	760	>99	-
LDD + 24 ppm NO_2 (13)	1.5	710	>67	-
Used motor oil (27)	0.7	19	4.8	-

Hayano (28) and Kittleson (29) have undertaken studies to directly sample exhaust from a combustion chamber. Hayano found that the concentration of PAH in the combustion chamber was 200 times as high as those in the exhaust gas. This study suggests that the PAH were produced during combustion in the combustion chamber and decomposed during the exhaust process. Kittleson found that 1-nitropyrene is formed primarily during the expansion stroke and/or in the exhaust manifold.

PARTICLE/GAS PHASE DISTRIBUTION

The distribution of the emissions between the gas-and particle phase is determined by the vapor pressure, temperature and concentration of the individual species. The partitioning of constituents between the particulate- and gas- phases have been measured by several investigators (2,30-33). Based upon this data an empirical relationship was derived for the boiling point and the particle- to gas-phase partition coefficient (P/G) for several compounds of different molecular weight. It was found that a linear relationship exists between boiling point for the various PAH compounds and the aliphatic hydrocarbons as shown in Figure 1. This relationship was used in our study to calculate gas-phase emission rates for three of the candidate compounds from the particulate- phase emission rates (Table 7).

TABLE 7

PARTICLE TO GAS PHASE DISTRIBUTION (P/G) VALUES FOR THE CANDIDATE COMPOUNDS

Compound	MW	Distribution Factor (P/G)
anthracene	211	0.05
pyrene	202	0.75
fluoranthene	202	0.75

Van Vaeck et al., (34) and others have shown that the distribution of particle to gas-phase components increases as the temperature decreases but the magnitude of this effect is difficult to assess in greater detail without additional data.

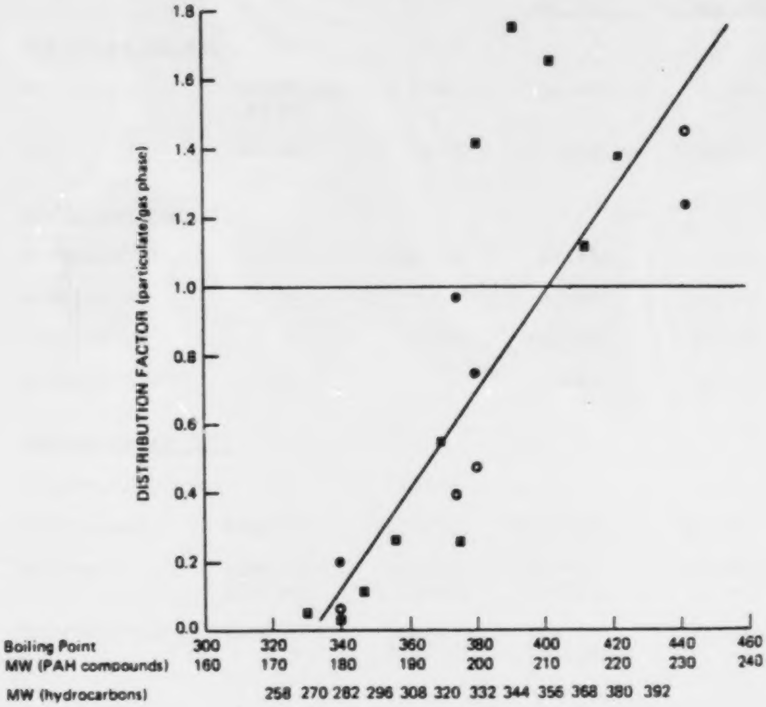

Figure 1 (● ref. 7; 0 ref. 13; ■ ref. 30)

EMISSION LEVELS FOR CANDIDATE COMPOUNDS

A number of studies have been undertaken during the past five years to determine emission levels for a wide variety of vehicles. Emission levels for the sixteen candidate compounds, mutagenicity, and total particulates from (1980-1985) light-duty diesel, heavy-duty diesel, gasoline engines (with catalyst) and gasoline engines (without catalyst, 1973-1981) are summarized in Table 8. The emission levels from all pertinent literature sources are given as an average of all values. These tabulated values can serve as a basis for semi-quantitative studies of exposure.

TABLE 8

A SUMMARY OF EMISSION LEVELS FROM CURRENT (1980-1985) DIESEL AND GASOLINE ENGINES (FTP CYCLE ONLY)

Parameter	HDD	LDD	Gasoline Car	
			No Cat.	Catalyst
Gas-phase (g/mi)				
CO	10(36,23)	3(37)	15(39)	5(35)
	8(35)	-	-	-
NO_x	28(35)	1(37)	4(38)	2(35)
Gas-phase (mg/mi)				
formaldehyde	-	20(39)	56(39)	4(39)
propylene	-		230(40)	18(40)
benzene	-	24(39)	162(39)	13(39)
toluene	11(40)	-	215(40)	32(40)
Gas-phase (μg/mi)				
2-nitrofluorene	-	90(7)	-	-
anthracene	8960(37)	2100(37)	3200(37)	60(37)
pyrene	1580(37)	380(37)	580(37)	9(37)
	1580(41)	1130(41)	200(41)	-
fluoranthene	1240(37)	300(37)	450(37)	7(37)
	-	910(7)	300(18)	-

TABLE 8 (cont.)

Parameter	HDD	LDD	Gasoline Car No Cat.	Gasoline Car Cat. (3-way)
Particle-phase (µg/mi)				
anthracene	439(37)	105(37)	160(37)	3(37)
pyrene	1182(37)	284(37)	431(37)	7(37)
	-	848(7)	150(18)	-
	-	284(41)	19(35)	10(35)
	-	39*	47(39)	26(39)
fluoranthene	933(37)	224(37)	340(37)	5(37)
	-	683(7)	225(19)	-
	-	933(41)	224(41)	-
2-nitrofluorene	-	97(7)	-	-
1-nitropyrene	45(37)	11(37)	0.3(37)	<0.1(37)
	-	4*	0.2(35)	0.2(35)
benzo(a)pyrene	54(37)	13(37)	20(37)	0.4(37)
	-	1*	5(39)	-
		3(41)	2(42)	0.1(42)
	-	-	15(35)	3(35)
	142(41)	34(41)	-	-
benzo(e)pyrene	64(37)	15(37)	23(37)	0.4(37)
	-	3*	3(39)	-
Other Emissions				
Total Part. (mg/mi)	1660(7)	394(7)	99(7)	18(7)
	1490(35)	607(35)	103(35)	32(35)
Total Ext. (mg/mi)	301(7)	198(7)	16(7)	10(7)
	335(35)	124(35)	21(35)	14(35)
Mutagenicity** (rev./mi/10^{+6})				
TA98 (-S9)	0.37(7)	0.95(7)	0.10(7)	0.05(7)
		0.99*	0.15(35)	0.04(35)
TA98 (+S9)	0.33(7)	0.36(7)	0.22(7)	0.07(7)
	-	0.59*	0.26(35)	0.08(35)

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*Table 3, this report (22% fuel aromaticity)

**Mutagenicity values given in Table 8 of Ref. 7 should be given as rev/km x 10^{-3} instead of rev/km.

ATMOSPHERIC REACTIONS

Several of the compounds listed in Table 1 may undergo atmospheric conversion to potentially hazardous products that may have significant toxicological importance. Nitrogen oxides (e.g.

NO_3, N_2O_5), O_3 and free radical species (e.g. OH, NO_3) can react with gas-phase hydrocarbons (e.g. propylene) and aromatic hydrocarbons (e.g. toluene, anthracene, pyrene, fluoranthene and BaP) to produce nitrated, peroxynitrated and oxygenated derivatives. These six candidate compounds were chosen because they are representative of the types of compounds in vehicle exhaust which could undergo atmospheric transformations. The chemistry and identification of these reaction products have been summarized recently by Finlayson-Pitts and Pitts (43) and Atkinson (44).

1-Nitropyrene is one of the more predominant nitrated-PAH compounds in vehicle exhaust. There is no significant formation of this compound in the atmosphere. In addition, this compound is relatively stable (45) and therefore could serve as a good tracer for primary combustion sources, especially vehicle sources.

2-Nitropyrene (2-NP) has been identified in ambient air particles but not in vehicle emissions (46). This compound is formed in the atmosphere from the gas-phase reaction of the OH radical in the presence of NO_x with pyrene (47). In conclusion, 2-NP could be used as a good tracer for determining the degree to which gas-phase species have been chemically converted into particle-phase components. The concentration ratio of pyrene/2-NP in the particles could be used for this purpose.

Table 9 lists some ratios of PAH concentrations obtained from a number of ambient air particulate sources. These ratios can be used to estimate the relative contribution of vehicular emissions to PAH in ambient air particulates and the stability of the PAH in these samples.

The fluoranthene/pyrene ratio is nearly constant for ambient air (~1.2 average for all sites) and combustion emission (~1.1 average) particulates, irrespective of their source. Since pyrene is more reactive than fluoranthene (25) it would appear that PAH are stable once they are absorbed on particulates.

The BeP/BaP ratio shows little variation (~1.9 average) for ambient air particulates, irrespective of the sample source. However, this ratio varies for particulates emitted from combustion sources. As discussed previously, BaP is more reactive than BeP but the BeP/BaP shows little variation in ambient air samples. Thus it can be concluded that once the PAH are absorbed on particulates they do not undergo any significant degradation in the atmosphere. Two of the samples, NBS-SRM1648 and NBS-SRM1649, were collected over periods of several hundred hours. However, the PAH ratios are not significantly different from samples collected for 24 hours or less. The samples collected in Norway were transported from other parts of Europe and therefore had 2 or 3 days to undergo conversion. However, the pyrene/BaP ratios in these samples did not differ much from those for other rural samples.

The data for pyrene/BaP ratios presented in Tables 5 and 9 can be used to determine the relative contribution of diesel emissions to PAH in ambient air particulates. The average pyrene/BaP ratios for LDD and HDD vehicles averaged 30 and 23, respectively, compared to 1.8-2.2 for gasoline powered vehicles, while the ratio for all urban samples averaged 1.7. It can be concluded from these data that the diesel engine has had little impact on the concentration of PAH particulate species in U.S. urban environments. The ratio of pyrene/BaP for European urban samples is 2.6 which would be consistent with the higher proportion (compared to the U.S.) of diesel vehicles. The higher values of pyrene/BaP for rural locations (4.1) may be due to contributions from other sources such as wood smoke. Based upon the analysis of PAH ratios in atmospheric samples, it appears that most of the PAH found in U.S. urban particulates originate predominantly from light-duty gasoline (LDG) vehicular sources as based upon the ratios of fluoranthene/pyrene, pyrene/BaP, and BeP/BaP for U.S. (1.0, 1.7 and 2.0, respectively) compared to these ratios in LDG particulates (1.1, 2.0, 1,8, respectively), assuming a 1/1 mix of catalyst and non-catalyst vehicles. However, these observations need further validation since our data base for other primary emission sources (Table 9) is limited, and data on PAH ratios were not available. For instance, reliable PAH emission values from residential oil burning sources were not available.

TABLE 9

RATIOS OF PAH CONCENTRATIONS OBTAINED FROM A NUMBER OF AMBIENT AIR PARTICULATE SOURCES

Sample Source (ref.)	Flu/Pyr	Pyr/BaP	BeP/BaP	Pyr/1-NP
Air Particulates (urban)				
Europe				
Germany (48) (5 sites)	1.6	3.9	2.0	-
Goteborg, Sweden (49)	1.1	2.1	2.1	-

TABLE 9 (cont.)

Sample Source (ref.)	Flu/Pyr	Pyr/BaP	BeP/BaP	Pyr/1-NP
Denmark (50)	0.9	2.2	1.0	140
Sweden, urban (49)	1.0	2.3	2.1	-
Average	1.2	2.6	1.8	-
United States				
Wash. D. C. (NBS-SRM1649)(51)	1.1	2.4	1.3	75
St. Louis (NBS-SRM1648)(51)	1.2	2.4	1.7	-
Los Angeles (12)	1.0	1.0	2.4	-
Los Angeles (52)(3-41)	1.4	1.9	2.6	-
Los Angeles (53)	0.7	1.0	2.0	-
Detroit (54)	0.8	1.7	-	-
Average	1.0	1.7	2.0	-
Air Particulates (rural)				
Baltic Sea (48)	1.9	6.3	2.8	-
England/Scotland (55)(2 sites)	1.3	3.3	1.2	-
Norway (55)(2 sites)	1.2	2.6	1.3	-
Midwest, Northeast(52)(3-20)	1.5	4.3	1.9	-
Average	1.5	4.1	1.8	-
Other Sources				
Power plant-coal(56)	1.6	3.0	-	-
Coke oven (57)	1.0	1.0	0.7	-
Wood Smoke (58)	1.1	-	-	-
Wood Smoke(58)(reacted)	1.1	-	-	-
Wood Smoke (59)	1.4	6.9	6.9	
Carbon Black (60)	0.6	2.2	0.8	-
Coal oven (Heinrich, this volume)	1.4	2.8	0.7	-
Aluminum smelter (61)	1.6	0.8	3.0	-
Average	1.2	-	-	-

ESTIMATION OF EXPOSURE LEVELS

There are many existing models for describing exposure levels (2, 62-65). The annual mean concentration of gas and particulate phase components in a selected location can be estimated by tracer or surrogate models (2, 62). The model uses CO as the tracer for gas-phase components and assumes that, under similar dispersion conditions, the proportionality between the ambient concentration of CO and the emission rates of carbon monoxide and the subject nonreactive airborne species is similar for all chemical species. The emission levels presented in Table 8 can be used in a comparative way to determine the relative impact of diesel and gasoline engine emissions if information on the proportion of vehicular types in a particular area is known.

TOXICOLOGICAL DATA

Several of the candidate compounds were chosen on the basis of current knowledge or interest in the area of potential toxicological effects. These compounds include CO, NO_x, formaldehyde, propylene, benzene, 2-nitrofluorene, benzo(a)pyrene and 1-nitropyrene (and the dinitropyrenes). Several studies have been undertaken by the NAS and others and their findings are summarized as follows:

Carbon Monoxide - CO exposure can cause acute and chronic effects on susceptible populations (66,67). CO binds to haemoglobin in the blood with an affinity 200-250 times greater than oxygen thus affecting the capacity to oxygenated body tissues. Because of this greater affinity for haemoglobin binding, CO releases slowly and consequently incremental doses of CO from different exposure sources are additive. Individuals with intermittent claudication, cardiovascular problems (angina), emphysema, asthma, sickle cell anemia, and other diseases that may cause reduced oxygen tension in the blood, have an increased risk due to CO exposure.

NO_x - NO_2 is the major NO_x species on which most toxicological studies have been undertaken (68). Studies of short-term exposures of firemen have shown increased airway resistance, decreased pulmonary diffusion capacity, increased alveolar arterial partial oxygen pressure difference and conditions such as diffuse pneumonitis. In most epidemiological studies there are other pollutants present and their combined effects are impossible to separate from those of NO_2. There is a time dependent continuum of effects ranging from mild reversible and irreversible effects in pulmonary function to more severe short-term substantial chronic tissue damage, functional impairment and aggravation of other disease processes. Reported results of epidemiologic studies in children are increased incidence of respiratory disease (upper and lower), greater incidences of bronchitis, and adverse effect on specific airway conductance. Persons who might be operating at or near the limit of their pulmonary functional capacity or sensitive persons, asthmatics, might experience chest tightness or wheezing.

The U. S. Environmental Protection Agency (EPA) standard for atmospheric concentrations is 0.053 ppm annually. A short-term exposure standard is currently being considered by EPA.

Formaldehyde - There have been numerous studies of the irritant properties of formaldehyde showing that the eyes, respiratory tract, and skin are the organ system predominantly affected (69). Formaldehyde has been shown to be mutagenic in several nonmammalian test systems, such as microorganisms and insects, but negative in the Ames test and there have been conflicting findings in mammalian test systems. Similarly, the results of long-term experimental studies in animals on the carcinogenic effects of exposure to formaldehyde have been brought into question. Although some experimental studies have shown nasopharyngeal carcinoma in animals, other studies have not shown these effects. There are people known to be sensitive to formaldehyde exposure who do react adversely but there are no systematic studies of them. At present, the irritant effects appear to be the most sensitive responses to formaldehyde exposure.

Benzene - Benzene has been designated as a "hazardous air pollutant" by EPA and a "toxic air contaminant" by the California Air Resources Board. Based on human epidemiologic evidence, benzene exposure is associated with an increased incidence of certain forms of leukemia, as well as a variety of other cancers (70). The lowest average concentration of benzene vapor reported to have been associated with human leukemia and aplastic anemia is 1 ppm and 5 ppm, respectively. There is an increasing amount of evidence that indicates latent diseases such as cancer, birth defects, and genetic disease may be initiated by alterations in cellular DNA resulting from benzene exposure. A number of studies have shown that benzene is not mutagenic in bacterial systems. Benzene has not been shown to be teratogenic at doses that are feto-lethal.

2-Nitrofluorene - This compound has been found to be carcinogenic for subcutaneous exposure to rats (47% tumor incidence). It was found to induce a high incidence of papillomas and carcinomas of the forestomach and it is carcinogenic in rats when administered either in food or painted on the skin in a 2% acetone solution. More tumors were induced by skin application than by ingestion in the food (71).

Benzo(a)pyrene - The 1983 IARC (72) report concluded that BaP is carcinogenic and teratogenic in mice; the induction of aryl hydrocarbon hydroxylase activity in fetuses is an important factor in determining these two effects. Also, reactive electrophiles are formed in the metabolism of BaP that are capable of binding covalently to DNA, however, the importance of this finding is not known at this time.

In short-term bioassays, BaP is active in bacterial DNA repair, bacteriophage induction and bacterial mutation; it forms mutations in Drosophila elanogaster. It was found to be active in DNA repair, sister chromatid exchange, chromosomal aberrations, point mutations and transformations in mammalian cell cultures. BaP was active in chromosomal abberation, sister chromatid exchange, DNA, sperm abnormalities and in the somatic specific locus (spot) test.

A 1983 NRC study showed several metabolic sites on the molecule where epoxides could be formed. The primary precursor implicated was the 7,8-diol which in the second round forms the highly electophilic 7,8-diol-9,10-epoxide.

BaP may not be the best indicator of the biologic effects of other PAH, however, the literature on this compound is considerably more voluminous than that on other PAH.

1-Nitropyrene - This compound has been found to be a weak carcinogen in rats (73). The dinitropyrenes are active carcinogens as described by Tokiwa et al., Sato et al, King et al and Odagiri et al in this volume.

RISK ASSESSMENT

At this time there is sufficient information on the sixteen candidate compounds to begin applying semi-quantitative and comparative risk assessment models. However, we recommend that biomarker techniques need to be developed for several of the compounds to determine actual exposure.

Mutagens and cancer initiators act directly or are metabolized to electrophilic reagents. At the molecular level these react in a random fashion, with probabilities determined by reaction kinetics laws, with nucleophilic centers (mainly S, N and O atoms) in tissues. The degree of chemical change (e.g. alkylation) could be demonstrated to be proportional to exposure doses (or absorbed amount per kg body weight) in proteins (74) or DNA (75).

Although DNA is the biological target in genotoxic action, haemoglobin (Hb) is a better media for monitoring or dosimetry of electrophiles. Since Hb has a life-span of approximately 4 months in healthy individuals, it can be used to determine the integrated exposure dose during that period of time. In addition, it is relatively easy to obtain. Amino-acid adducts are more easily determined and identified than DNA-base adducts.

The Advisory Subgroup on Toxicology (AST) of the European Medical Research Councils (EMRC) has evaluated the "Hb adduct method" and concluded that it gives relevant information on the formation of DNA adducts.

Haemoglobin adducts have been used to monitor exposure to alkenes such as propylene, NO_2 and approximately 50 carcinogens. Work is underway to study the effects of vehicle emissions on adduct formation (76).

Mass spectrometric methods are being developed which allow the determination of down to 1 ppb of a component in blood (76, 77). This adduct level could be expected by occupational exposure to about 0.01 ppm ethylene oxide. However, determination of exposure to compounds such as PAH and PAH-derivatives will require detection limits below the 50 ppt range, a level which is not currently attainable.

Breath analysis is a technique that potentially can indicate the extent to which an individual has been exposed to gaseous pollutants. As an example, a recent study has been undertaken to help estimate exposure to ambient air levels of benzene (79). In some cases it was found that the level of expired benzene was greater than that of the ambient air concentration. It will be difficult to quantitatively determine exposure to gaseous pollutants using this technique since the dynamics of inhalation, absorption, metabolism and exhalation are not well understood.

CONCLUSIONS

A number of conclusions can be made as a result of the data presented in this paper as follows:

- -Dilution tube sampling of vehicle emissions yields reliable data which can be used to estimate ambient air exposure levels to gas and particulate phase pollutants.
- -Sixteen candidate compounds have been chosen for detailed study and gas-and particle-phase emission levels for these candidate compounds have been compiled for diesel and gasoline powered engines.
- -The concentration of these candidate compounds can vary by

several times, depending upon vehicle operating conditions.

-PAH appear to be formed primarily as a result of the combustion process and not due to the content of unburned fuel in the exhaust.

-An increase in fuel aromaticity results in increased emission of PAH and total mutagenicity.

-The concentration ratio of pyrene to BaP in particulates can be used to estimate the contribution of diesel emissions to PAH in ambient air particulates. It was demonstrated that diesels contribute less than 10% of the total PAH found in U.S. urban particulate matter.

-The chemical components emitted in the particle phase from vehicles undergo very little chemical conversion in the atmosphere.

-The gas-phase components of intermediate volatility (C_6-C_{16}) may undergo significant chemical conversion to form particulate species of potential toxicological significance.

-The most difficult problem associated with the toxicology studies is extrapolation of high-level exposure data to the low concentrations encountered in ambient air environments.

-The measurement of haemoglobin adducts can be used to measure long-term integrated exposure to some gas-phase species such as propylene. However, these techniques are not sensitive enough at this time to measure exposure to trace components found in particulates (e.g., PAH and PAH-derivatives).

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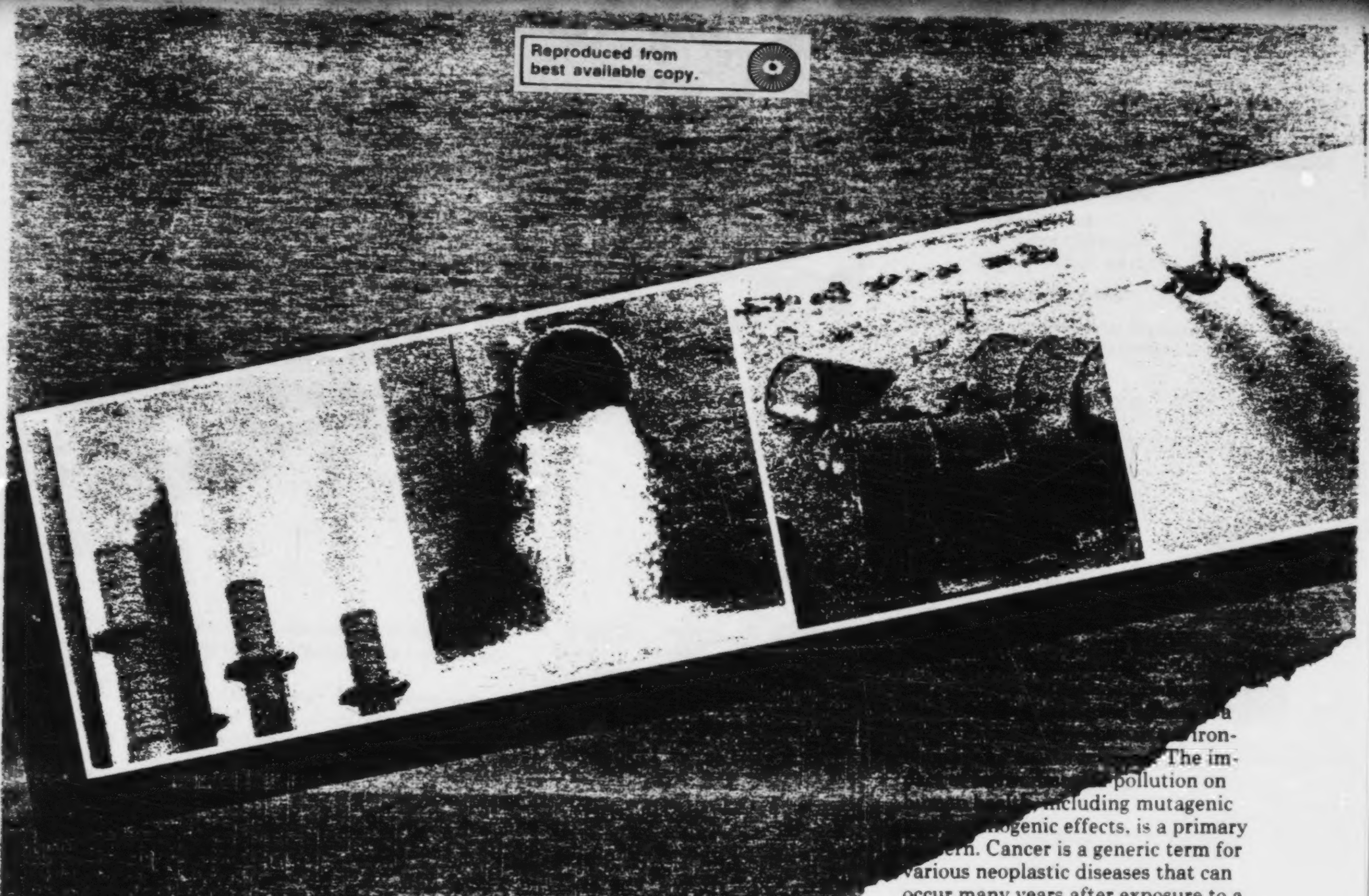

Bioassay-Directed Chemical Analysis in Environmental Reseach

[illegible] a [illegible] iron- [illegible] The im- [illegible] pollution on [illegible] including mutagenic [illegible] ogenic effects. is a primary [illegible] ern. Cancer is a generic term for various neoplastic diseases that can occur many years after exposure to a carcinogenic substance. The best means of eliminating cancer is to define precisely the nature of the carcinogenic chemical, mixture of chemicals, or enhancing factors in the environment that produce the cancer (*1*). Bioassay studies in the early 1960s showed that environmental mixtures such as cigarette smoke and ambient air particulates can cause cancer in animals. Extensive studies were undertaken to determine the chemical components that could be responsible for such an effect. It was found that most environmental samples were chemically complex and comprised of thousands of chemical compounds (*2, 3*). Identification of the most biologically active compounds presented an enormous if not an impossible task.

During the mid-1970s several microbial tests were developed that were simple, cheap, rapid, and above all genetically very well defined (*4*). The bacterial reverse mutation test battery in *Salmonella* as developed by Ames et al. (*5*) provided a vast body of information on the presence of genotoxic activity not only in defined industrial chemicals, pesticides, and cosmetics but also in complex mixtures such as air, water, and other complex sources of pollutants. Although this test, and others like it, were used to determine the relative mutagenic potency for a wide variety of environmental samples, such studies did not yield infor-

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Report

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mation on which specific compounds were primarily responsible for this activity.

The Ames tester strains were selected so that types of mutations (e.g., frame shift vs. base pair substitutions) can be distinguished. This information, together with differential responses (e.g., with and without microsomal activation), can be used to provide information about the general classes of chemicals causing the response. More recently, new tester strains that are sensitive to certain classes of chemical mutagens have been developed. For instance, strain TA98NR (Rosenkranz nitroreductase strain) is deficient in nitroreductase enzymes and therefore gives a reduced response to certain nitrated PAH compounds. The magnitude of results varies depending on the type of assay used, as shown for diesel particles in Table I. In addition, the contribution of an individual compound to total fraction mutagenicity is dependent on the type of bacteria used in the assay. These differences make it possible to apply these strains in a diagnostic way. Because strain TA98 has been used most frequently for assays of environmental samples, we will limit our discussion to its use in this REPORT.

Table I. Direct-Acting Mutagenicity of Diesel Particulate Extract (NBS SRM 1650)

Bacterial strain	Mutagenicity (rev/μg)
TA98	5.0
TA98NR	1.5
TA100	5.5
TA104	17.0

It became apparent in the late 1970s that these bioassays could be used in combination with chemical fractionation to greatly simplify the process of identifying significant mutagens in complex environmental samples, such as diesel particles, petroleum and petroleum substitutes, chemicals in drinking water (*6*), and commercial products (*7*). The use of short-term bioassays in conjunction with analytical measurements constitutes a powerful tool for identifying environmental contaminants. We have coined the term "bioassay-directed chemical analysis" to best describe this marriage of analytical chemistry and biology. The objective of this methodology is to identify key compounds in various types of air pollutant samples. Once that task is completed, studies on metabolism, sources, environmental exposure, and atmospheric chemistry can be undertaken.

The protocol for bioassay-directed chemical analysis illustrated in Figure 1 was developed originally in our laboratories during the late 1970s (*8, 9*) to identify chemical mutagens in diesel particulate extracts. At about the same time similar techniques for the identification of chemical mutagens in synthetic fuels were reported by Guerin et al. (*10*) and Wilson et al. (*11*) and in drinking water by Tabor et al. (*12*). More recently, these techniques have been used in a rigorous manner for the identification of mutagens in other types of air pollution samples, such as ambient air particulates, diesel particulates, and wood smoke (*13–15*), and in water pollution samples such as river water (*16*). Most of our work has been directed toward the characterization of ambient air and diesel particulates. We will use these examples to illustrate the analytical logic used in identifying the mutagenic components of complex mixtures.

Proper sampling, storage, and extraction of an environmental sample are crucial parts of the analysis. If the sample is not qualitatively and quantitatively representative of what is present in the environment, results obtained from the bioassay-directed chemical analyses are of little value in assessing environmental risk. However, it is not necessary to use a representative sample to develop methods. Some selected large samples collected in early studies were used for methods development. Since that time, the National Bureau of Standards (NBS) has made available a number of environmentally related reference materials that are useful in developing bioassay-directed chemical analysis techniques. These materials were not meant to be representative samples from which conclusions could be made concerning their origin or environmental risk. The major advantage of this approach is that a common and representative material is available to many laboratories for intercomparison of results. Two materials that have been used most widely for this purpose are NBS SRM 1650 (heavy-duty diesel particulates) and NBS SRM 1649 (ambient

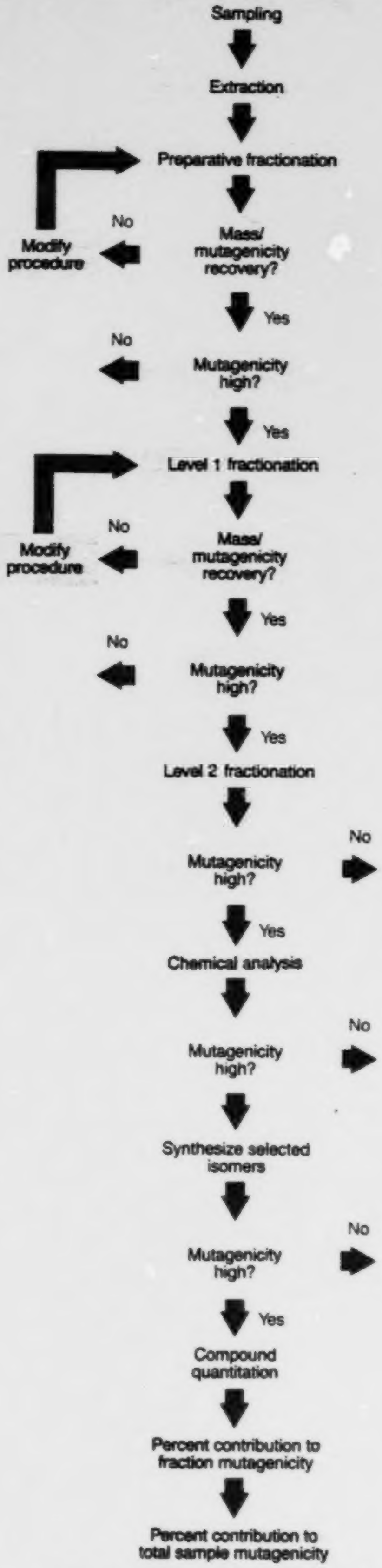
Sampling
Extraction
Preparative fractionation
Modify procedure
No
Mass/ mutagenicity recovery?
Yes
No
Mutagenicity high?
Yes
Level 1 fractionation
Modify procedure
No
Mass/ mutagenicity recovery?
Yes
No
Mutagenicity high?
Yes
Level 2 fractionation
No
Mutagenicity high?
Yes
Chemical analysis
No
Mutagenicity high?
Synthesize selected isomers
No
Mutagenicity high?
Yes
Compound quantitation
Percent contribution to fraction mutagenicity
Percent contribution to total sample mutagenicity

Figure 1. Protocol for bioassay-directed chemical analysis

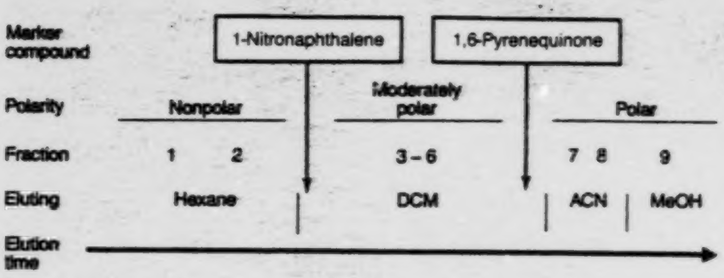
Marker compound
1-Nitronaphthalene
1,6-Pyrenequinone
Polarity
Nonpolar
Moderately polar
Polar
Fraction
1
2
3 – 6
7
8
9
Eluting
Hexane
DCM
ACN
MeOH
Elution time

Figure 2. Designation of nonpolar, moderately polar, and polar fractions using normal-phase HPLC in the level 1 fractionation scheme

air particulate matter collected in Washington, D.C.).

Extraction

Sequential extraction with increasingly polar solvents, binary solvents, and supercritical fluid extraction are used to separate organic material from particulates and other types of solid environmental samples. A two-step extraction process using methylene chloride followed by methanol is effective for efficient recovery of mutagenicity and mass for several types of combustion emission samples. Liquid-liquid extraction using dichloromethane and diethyl ether is suitable for extraction of mutagenic material from heavily polluted waters. Adsorption of pollutants on resins followed by solvent elution is effective for concentrating organics that are present in low concentrations (*17*).

Preparative fractionation

A number of prefractionation and preseparation techniques have been developed to help simplify the analysis of environmental samples. They are usually applied on a preparative or semipreparative scale to yield gram to milligram quantities, respectively, of samples. The two most widely used techniques are chromatography on an open normal-phase silica column to separate groups of compounds on the basis of polarity and separation of compounds into acidic, basic, and neutral fractions.

Early attempts to chemically characterize the trace components in sample fractions proved to be extremely difficult, and it was estimated that hundreds of compounds were present. However, bioassay analysis helped researchers decide which fractions should be studied in more detail (Figure 1).

One of the concerns of the early work in the late 1970s was the potential loss and formation of mutagenic substances during analysis. The procedural recovery of mass and mutagenicity is determined by combining the individual fractions to produce a reconstituted sample. The mass and mutagenicity of this sample are then compared with that of the unfractionated sample. Another test is to determine if the biological activity of the unfractionated sample equals the sum of the activities of the individual fractions. If they are unequal, the mutagenicity may be due to synergistic or toxic effects or to the fact that cell killing was not taken into account. If the separation removes highly toxic components from the mutagenic components, the additivity of the fraction mutagenicities may be greater than 100%. Any bioassay that has enough sensitivity to obtain good quantitative results (*6, 13*) on small (microgram) quantities of material can be used in the bioassay-directed chemical analysis technique.

Level 1 fractionation

Normal-phase high-performance liquid chromatography (HPLC) is a highly reproducible technique that separates environmental samples into chemical fractions of increasing polarity using hexane, dichloromethane (DCM), acetonitrile (ACN), and methanol (MeOH) as eluents (*8*). The reference materials 1-nitronaphthalene and 1,6-pyrenequinone may be used as chemical markers to designate the separation of samples into nonpolar (1–2), moderately polar (3–6), and polar (7–9) fractions (Figure 2). Results from a number of laboratories using slightly different fractionation procedures can be compared using this definition of polarity (*18*). It was found that the nonpolar fractions accounted for less than 2–3% of the total extract mutagenicity and that the distribution of moderately polar and polar materials was dependent on the sample source (Figure 3).

Table II gives the distribution of mass and mutagenicity for nonpolar, moderately polar, and polar fractions of NBS SRM 1650. Although 54% of the recovered mutagenicity is associated with polar compounds (fractions 7–9), the additivity of mass (94%) and mutagenicity (79%) is good. Diesel

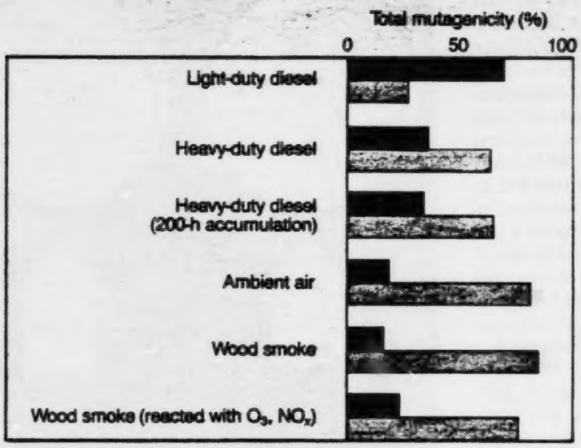

Figure 3. Distribution of mutagenicity (direct-acting TA98) between the moderately polar (green) and polar (blue) mutagenic fractions for six air particulate samples

particulate extract samples usually yield mass and mutagenicity additivities of greater than 90% and 70%, respectively, and mass and mutagenicity recoveries of better than 90%.

Chemical analysis

Studies were undertaken in the late 1970s to determine the composition of samples collected from the level 1 fractionation. High-resolution capillary column gas chromatography (GC) with selective detectors and coupled with mass spectrometry (GC/MS) proved to be powerful tools for the characterization of fractions.

By 1980 several laboratories, applying the techniques described so far, simultaneously made some important discoveries. Guerin et al. (*10*) and Wilson et al. (*11*) discovered the presence of highly mutagenic polynuclear aromatic amines (PAH–NH_2) in synfuels; Schuetzle et al. (*8*) found a significant mutagen, 1-nitropyrene, in diesel particles; and Lofroth et al. (*19*) and Rosenkranz et al. (*20*) identified 1,3-, 1,6-, and 1,8-dinitropyrenes as the major mutagenic substances in commercial carbon blacks. The amines and dinitropyrenes accounted for more than half of the sample mutagenicity in the case of the synfuels and carbon blacks, respectively. However, less than 25–30% of the mutagenicity of diesel particles could be accounted for by the 1-nitropyrene.

In the case of SRM 1650, GC and GC/MS analysis showed that hundreds of compounds were still present in each fraction. Figure 4 depicts a portion of a chromatogram generated

Table II. Mass and Mutagenicity Distribution (TA98, Direct Acting) for NBS SRM 1650[a]

Fraction	Distribution of mass (%)	Distribution of mutagenicity (%)
Nonpolar		
1	0.6	0
2	0.7	0
Moderately polar		
3	1.3	0
4	2.6	19
5	2.4	10
6	1.3	7
Polar		
7	3.7	24
8	41.6	9
9	39.8	10
Percent recovered	94.0	79

[a] Data from Reference 18

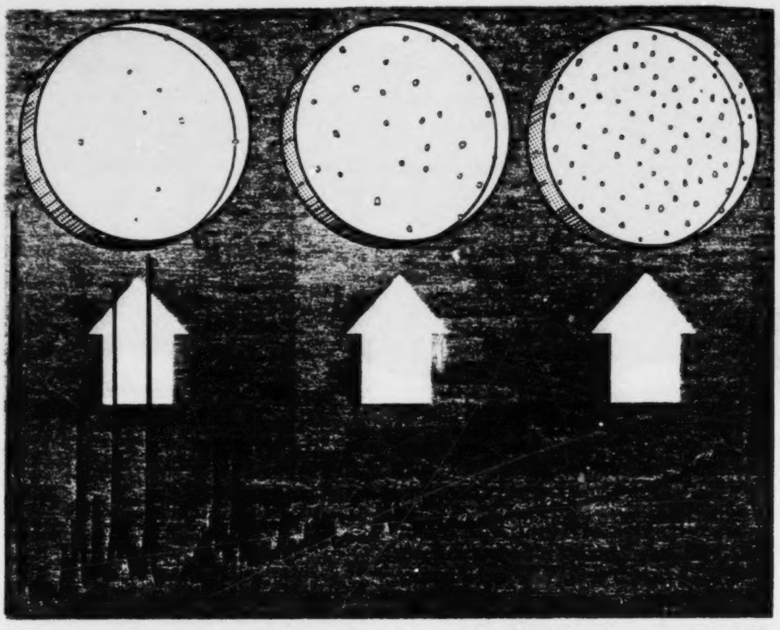

Figure 4. Capillary gas chromatogram of fraction 5 of a light-duty diesel sample with nitrogen-selective detection

Petri dishes at top illustrate results of Ames assays of subfractions of the diesel sample fraction

from the capillary column GC analysis of fraction No. 5 of a light-duty diesel sample using a nitrogen-selective detector. Scores of nitrogen compounds were found to be present in this fraction. GC/MS analysis verified that most of the nitrogen-containing compounds were nitrated polynuclear aromatic hydrocarbons (nitro PAHs). Ames assays of subfractions of fraction No. 5 showed that most of the mutagenicity was associated with compounds that eluted in the last one-third of the chromatogram.

Further analysis was made using direct-probe high-resolution mass spectrometry, high-resolution GC/high-resolution MS, and mass spectrometry/mass spectrometry (MS/MS). An important finding in these studies was that the moderately polar chemical fractions primarily consisted of substituted PAH compounds with ring sizes of 2–6 and the substituents consisted of hydroxy, aldehyde, anhydride, nitro, ketone, dinitro, and quinone functional groups (*8*). A potentially important group of mutagens, the nitrohydroxypyrenes, was identified in these studies (*21*).

Although a multitude of compounds were identified or tentatively identified, it was obvious that such fractions were still too complex to allow identification of chemical mutagens and that further separation of each fraction into subfractions would be necessary.

Level 2 fractionation

Further developments in HPLC, high-performance thin-layer chromatography (HPTLC) (*22*), and mutagenicity testing (*23*) have contributed to a much finer tuning of this combined chemical and biological approach to the characterization of mutagens in environmental samples. HPLC can generate scores of fractions, each of which is tested for mutagenicity. We refer to this resulting relationship of fraction mutagenicity to

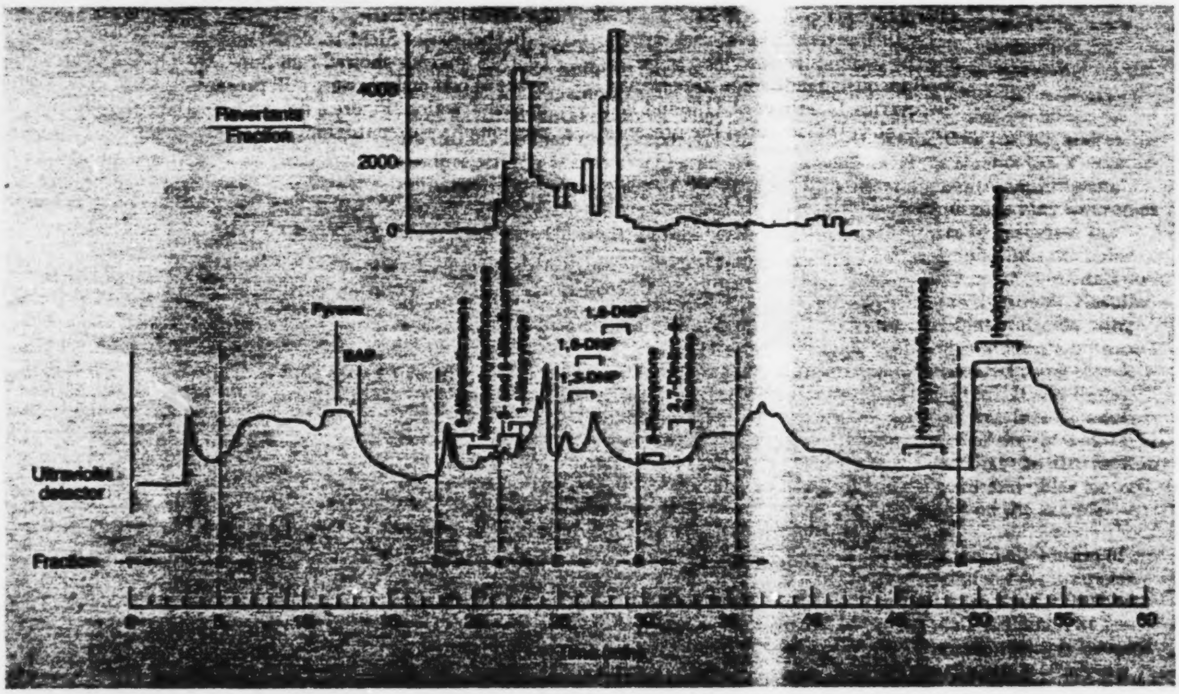

Figure 5. Ames assay chromatogram (TA98, without activation) and HPLC–UV analysis of a light-duty diesel particulate extract (level 1 fractionation)

[redacted]

fraction elution time as a bioassay chromatogram or an Ames assay chromatogram in cases in which the Ames test is used (*24*). A bioassay chromatogram for a diesel particulate sample is illustrated in Figure 5. The lower portion of the figure shows the corresponding HPLC chromatogram using a UV detector. The most mutagenic fractions have elution times that approximately coincide with 1-nitropyrene, 3-nitrofluoranthene, 8-nitrofluoranthene, 1,3-dinitropyrene, 1,6-dinitropyrene, 1,8-dinitropyrene, and 2,7-dinitro-9-fluorenone reference compounds.

GC/MS is a powerful technique for quantitative analysis of these trace constituents. Deuterated standards are added to the extracts before sample analysis, and quantitative results are readily obtained by comparing the signals from the eluting native and deuterated compounds. On the basis of such analysis it was found that 30–40% of the total recovered extract mutagenicity of SRM 1650 was attributable to the seven moderately polar nitro PAHs. The remainder of the mutagenicity (10–15%) was attributable to the presence of an unidentified compound or compounds eluting between 23 and 26 min; 30–35% was recovered in the polar fractions, and 5–10% was distributed about equally among the remaining fractions.

Although separation of the sample into acid, base, and neutral fractions is usually done in the early stages of sample preparation, this procedure can be used to further simplify the polar fractions. As an example, some preliminary data on the distribution of mutagenicity for the acid, base, and neutral fractions 7, 8, and 9 of SRM 1650 are given in Table III. This analysis shows that the most mutagenic compounds in the diesel sample are neutral in character. The additive mutagenicity for the acid, base, and neutral fractions is close to that of the unfractionated fraction 7. However, the additive mutagenicity for fractions 8 and 9 exceeded 100%. It is postulated that these high recoveries are indicative of chemical changes that may have occurred during acid–base extraction or separation of toxic compounds from these fractions. High-resolution mass spectrometric analysis of fractions 8 and 9 shows that organic esters and acids of PAHs and aliphatic compounds are major components. Acid or base hydrolysis of PAH esters could account for increased mutagenicity.

The specific fractionation scheme that most effectively separates the mutagens from the nonmutagens while minimizing the destruction or creation of mutagens varies with the types of complex mixture being analyzed. Diesel emissions from different sources will vary in the amount of specific components but the general composition is sufficiently consistent to develop one approach to the bioassay-directed chemical analysis, although several may be equally effective.

The scheme used to identify mutagens in synfuels has concentrated on preparative separative techniques because large quantities of materials were needed for extensive biological and chemical characterization studies. A relatively high level of mutagenic activity was found in an 800–850 °F distillation fraction of a synfuel sample (*10*). Nitrogen-containing compounds were separated on an alumina column using $CHCl_3$/ethanol. Level 1 fractionation was accomplished on a silicic acid column. GC/MS was used to identify PAH-amines as the major mutagenic species in the synfuels.

Ambient air particulates contain more chemical components than most other types of environmental samples. For this reason, the identification of mutagenic species in ambient air particulates has been more difficult than in diesel emissions. However, bioassay-directed chemical analysis procedures are being used to single out some potential candidate compounds.

LC and HPLC fractionation used in combination with acid–base–neutral separation appears to be an effective protocol for this purpose, as illustrated in Figure 6 (*25*). Good recovery of mass (98%) and mutagenicity (86%) for an extract of the NBS SRM 1649 air particulate sample was obtained by elution of five fractions on silica gel using hexane, hexane–benzene, methylene chloride, methanol, and acidic methanol (*26*).

SRM 1649 was used to develop the

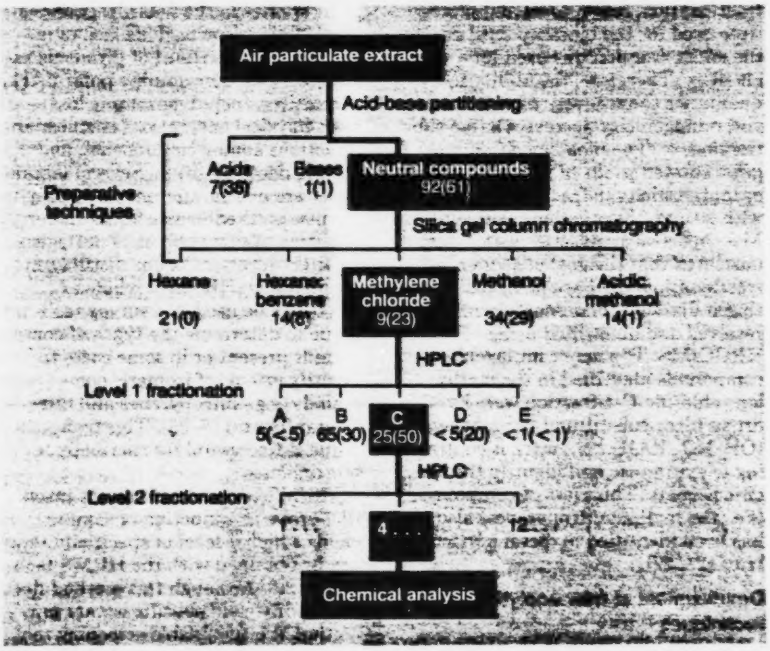

Figure 6. Bioassay-directed chemical analysis scheme for the analysis of NBS SRM 1649 (air particulate matter)

The numbers under each fraction represent the percentage distribution of mass and mutagenicity (in parentheses)

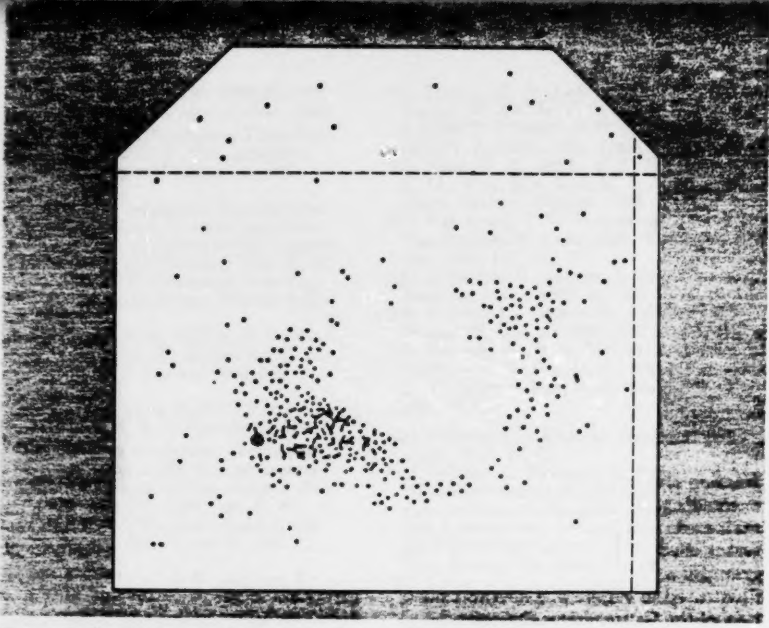

Figure 7. Distribution of mutagenicity for a combined Ames assay–HPTLC analysis of an ambient air particulate extract

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methodology for the ambient air samples. Once this methodology was developed, it was applied to fine air particles (<1.7 μm in diameter) collected in Philadelphia. The three fractions of greatest interest were the acid, methylene chloride, and methanol fractions, which produced 38%, 23%, and 29%, respectively, of the recovered mutagenicity (Figure 6). Because the methylene chloride fraction was more amenable to subfractionation by existing HPLC methods, this fraction was chosen for further fractionation. Normal-phase HPLC was used to fractionate the methylene chloride fraction (*26*).

The first HPLC subfractionation resulted in one fraction, methylene chloride-C, which contained nearly 50% of the mutagenicity in 25% of the mass. Analysis of this fraction by both electron impact and negative chemical ionization high-resolution (HR) GC/MS techniques indicated that the complexity of the sample was not reduced sufficiently to identify individual components. Subfraction C was further fractionated by normal-phase HPLC into 12 fractions for bioassay.

As we proceeded to higher levels of subfractionation, less and less mass was available for bioassay. In this study, the first-level fractions obtained from the preparative techniques were bioassayed in triplicate at seven doses with and without activation so that we could quantitate the distribution and recovery of mutagens. At the first and second levels of fractionation, fewer doses and plates were used for the bioassay until nearly the entire fraction was used for a single plate. Therefore, the ability to quantitate the recovery of both mass and mutagenicity decreases as we subfractionate. The bioassay chromatogram showed peaks of relatively higher mutagenicity in fractions 4 and 11 with 29 and 37 rev/μg, respectively. Mass spectral analysis of peak 4 demonstrated that the goal of sequential fractionation had been achieved such that individual components could be resolved and quantified using HRGC/MS. The major mutagenic compounds identified in the methylene chloride-C-4 fraction were hydroxy-nitro-substituted fluoranthenes (OH-NO_2-PAH) (*26*); work is continuing to synthesize and identify the specific isomers. This class of compounds (i.e., the hydroxynitropyrenes) also has been identified in diesel particulates (*21, 27*).

Development of new analytical techniques

Despite the considerable progress that has been made in determining moderately polar organics in environmental samples, there remain classes of compounds that have not yet been identified because of limitations in the analytical methods and detection systems.

There has been much less success with the determination of labile compounds (e.g., organic peroxides) and polar organic species. To date, only a limited number of compounds have been identified or tentatively identified as potentially important mutagenic species in the polar fractions of particulate extracts. This lack of information is the result of problems associated with determining polar PAH derivatives, including sample loss from physical adsorption, chemical interactions among components, and sample decomposition. Several laboratories are now developing and applying new methodologies for the determination of polar chemical mutagens.

Direct-insertion probe distillation coupled with HRMS of whole extracts can be used as a survey technique to determine the types of compounds present or in some cases to identify groups of isomeric compounds (e.g., nitropyrenes and nitrofluoranthenes) (*8, 28*). This technique is also useful for thermally labile organics.

MS/MS coupled with direct-insertion probe introduction of sample yields a higher level of specificity than can be obtained with the HRMS technique (*29*). Although this method does not readily yield specific isomer information, it is a valuable screening tool with a high degree of compound specificity. Secondary ion mass spectrometry (SIMS) using ion and neutral atom beams also may be useful for determination of polar and nonvolatile organic substances in environmental samples (*18*).

The above techniques are good for screening analyses. However, chromatographic separation is needed for positive identification of specific isomers in highly complex fractions. The poor recoveries GC and GC/MS achieve in the identification of polar compounds illustrate the limitations of GC techniques. One of the most promising analytical techniques for the determination of polar PAH derivatives appears to be supercritical fluid chromatography (*30*) and HPLC coupled with mass spectrometry (*31*).

New micromutagenesis methodologies that permit the quantitation of mutagenic activity on microgram quantities of material can now be used together with analytical-scale reversed-phase HPLC. The micro-forward mutation assay, which measures both mutagenicity and survival (toxicity), provides potentially more quantitation of a single-fraction mutagenicity (*32, 33*), whereas the micro-reverse suspension assay (*34*) uses the standard Ames and Rosenkranz strains. We have successfully coupled these assays to analytical reversed-phase HPLC separation and analysis of polar mammalian metabolites of nitropyrene. This approach shows great promise in helping to identify the polar mutagens in complex environmental samples.

Recently, techniques have been developed to couple liquid chromatography directly with bioassay analysis (*35, 36*). Duplicate (HPTLC) plates are used to fractionate organic matter.

One plate is used for chemical class tests and the second plate is used for an in situ Ames bioassay. This system has revealed some surprising and interesting differences among particulate matter samples from different cities. Figure 7 shows the distribution of mutagenicity for a combined Ames assay–HPTLC analysis of an ambient air particulate extract. Although the compounds responsible for the concentrated areas of mutagenicity are not known, it is envisioned that future advances in chemical analysis will help this effort. One such aid would be direct chemical analysis of the HPTLC plates using ESCA or SIMS to generate spatial chemical maps of the surface, which could be correlated with the pattern of mutagenicity.

In the future, a substantial effort will be needed to determine the compounds responsible for the mutagenicity of air and water pollutants. Bioassay-directed chemical analysis will continue to be a valuable tool for this purpose.

Acknowledgment

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The research described in this article was reviewed by the EPA and approved for publication. Approval does not signify that the contents necessarily reflect the views and policy of the agency.

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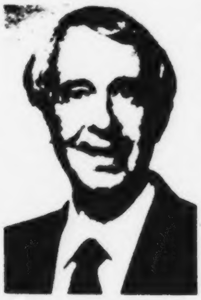


Dennis Schuetzle is a principal research scientist and head of the chemical research department of Ford Motor Company. He received his B.S. degree in chemistry in 1965 and interdisciplinary Ph.D.s in analytical chemistry and environmental engineering at the University of Washington. His primary research interests include environmental analytical chemistry, surface analysis, and process analytical chemistry.

Joellen Lewtas is chief of the genetic bioassay branch at the Environmental Protection Agency's Health Effects Research Laboratory. She received a B.S. degree in chemistry in 1966 and a Ph.D. in biochemistry from North Carolina State University in 1973. Her research has included evaluation of the mutagenicity and carcinogenicity of diesel and gasoline exhaust emissions and identification of mutagenically active components in these emissions.

Purposes

An independent organization designed –

- To serve as the nation's center for the study of health effects of motor vehicle emissions; and
- To narrow scientific disputes and separate scientific issues from policy issues.

Slide Presentation.................................Dr. Rashid Shaikh

Structure

- Joint and equal funding by EPA and by domestic and foreign vehicle manufacturers.

- Board of Directors:
  - Archibald Cox *(Harvard Law professor; former Solicitor General)*
  - Donald Kennedy *(Stanford President; former FDA Commissioner)*
  - William O. Baker *(Chairman Emeritus, Bell Laboratories)*
  - Charles Powers *(President, Clean Sites).*

- Health Research Committee: sets priorities for HEI's research program.

- Health Review Committee:- assures quality and critiques reports.

Status

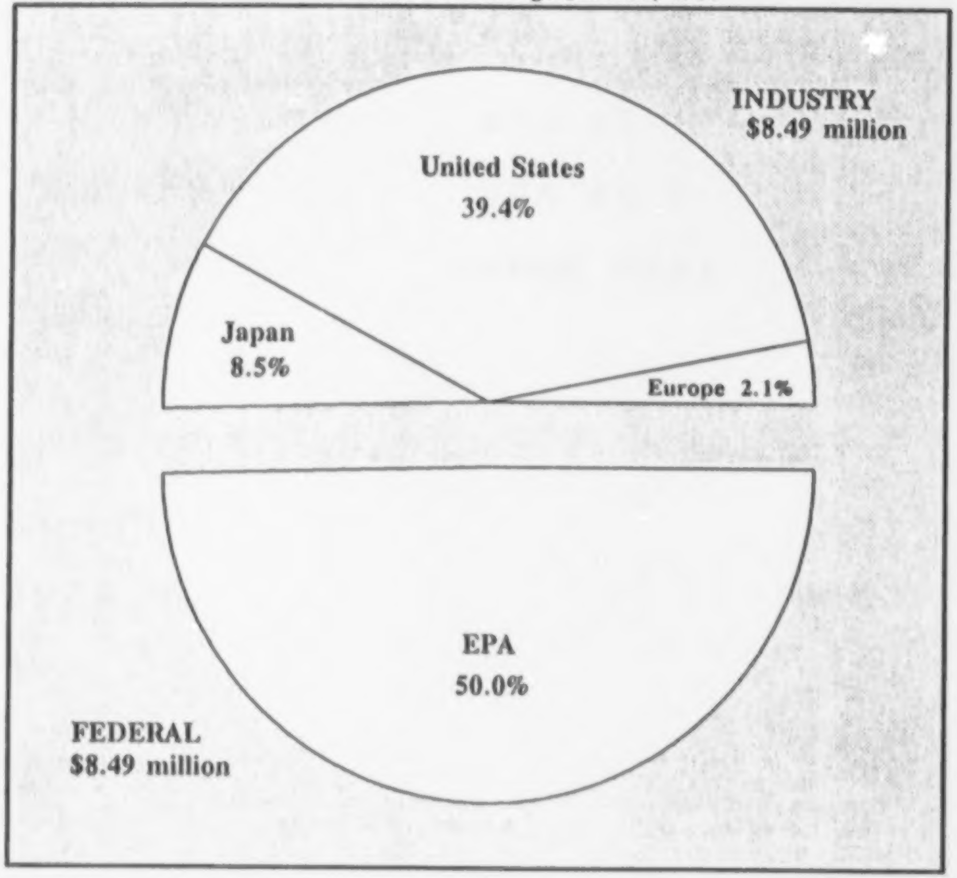
- Conducting 50 research projects on health effects of motor vehicle emissions.
- Sponsoring one–third to one–half of the world's research on this topic.

Selection of Research Projects

- **Consultation** – with HEI's sponsors, other government agencies, public interest groups, etc.
- **Competition** – among national and international applicants.
- **Coherence** – of individual projects within an integrated research plan.
- **Clearance** – of research priorities and reports by the Board of Directors.

SOURCES OF HEI SUPPORT

Cumulative Through June 30, 1986



THE HEI DIESEL PROGRAM

RFA 82-1

RFA 86-2

OTHER RFAs

COMPONENTS OF THE DIESEL PROGRAM

- Exposure assessment and characterization
- Hazard identification
- Dose-response relationship

Bagley:

EFFECT OF CERAMIC PARTICULATE TRAP:

- Caterpillar engine
- EPA Steady State operation in Modes 4 and 5
- Mode 4: 70% reduction in particulates
  45% reduction in mutagenicity
- Mode 5: 85% reduction in particulates
  25% reduction in mutagenicity

MAUDERLY:

- Susceptible groups:
  - The young
  - The emphysematous
- Fisher rats
- Chronic exposure to diesel emissions
- No difference in:
  - Lung structure
  - Lung function
  - Biochemistry
  - Cell types

MOON:

- Syrian golden hamsters
- 1-NP with carbon particles
- Intratracheal administration
- Adenomas, adenocarcinomas and squamous cell carcinomas

KING 1

- Female CD rats
- 1-NP, 1,3-, 1,6- and 1,8-DNPs
- SC injection
- Carcinogenicity:
  1,6- 1,8- 1,3-DNP 1-NP
- Malignant fibrous histocytomas
- Mammary gland tumors with 1,3-DNP

KING, CONT.

DO 1,6- AND 1,8-DNP PRODUCE MAMMARY TUMORS?

- Mammary gland tissue
- Nitro reduction: Same order as for carcinogenicity
- Adducts consistent with nitroreduction

THE CENTRAL DOGMA

PAH

CELLULAR
ENZYMES

TRANSFORMED
PAH

EXCRETION

DNA ADDUCTS

MUTAGENESIS

CARCINOGENESIS

JEFFREY AND MAUDERLY:

- F 344 rats, chronically exposed to diesel exhaust for 2.5 years
- Animals develop tumors
- DNA extracted from lungs
- Increased intensity of spots seen
- Consistent with a genotoxic mechanism for induction of tumors

FUTURE DIRECTIONS

- ROLE OF PARTICULATE MATTER
  - Modelling lung deposition
- MACROMOLECULAR ADDUCTS
  - Characterization and identification
  - Genetic consequences of DNA adduction
  - Biomonitoring
- OTHER STUDIES BEING PLANNED

For further information, contact

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Volume 4, Number 4 Sept/Oct 1986

A Publication of the Natural Resources Defense Council

NRDC Newsline

Settlement of Case Against GM Establishes Clean Bus Fuel Research Program

A unique program to perfect an engine for city buses powered by clean-burning methanol instead of diesel fuel has been instituted by NRDC, the Center for Auto Safety, the Environmental Protection Agency and General Motors. The cooperative program settles a major Clean Air Act enforcement case brought by NRDC against GM and EPA in 1982.

Under the agreement GM will conduct research and development over a three year period to improve the design and performance of current methanol engines. GM has agreed to give New York City, free of charge, six "first generation" methanol-powered buses. When a "second generation" of buses with improved engines are available, GM will sell up to twenty-six of them to New York City at the same price as a diesel bus.

Developing the methanol engine to replace the diesel is one of NRDC's highest priorities for protecting the health of city dwellers. Each year diesel vehicles dump thousands of tons of foul-smelling smoke and soot into urban air nationwide — more than three thousand tons in New York City alone. Diesel particles are inhaled into the deepest part of the lung where they can cause or aggravate serious lung diseases, including cancer. According to EPA data, present levels of diesel emissions may be causing up to 350 cases of

continued on page 4

Settlement of Case Against GM

continued from page 1

lung cancer every year. Diesel particles also cause millions of dollars in soiling damage to buildings, fabrics and other materials, and sharply cut urban visibility. If the methanol program succeeds, a vastly preferable alternative will soon be commercially available.

The dispute that led to this settlement began in 1982 when the EPA decided to let GM avoid its responsibility to recall and repair two models of 1979 Pontiacs which failed to meet emission standards. NRDC attorney David Doniger objected to EPA's alternative plan, in which the company would impose a marginally stricter standard on cars made in future years in order to "offset" the pollution increase.

Doniger doubted that the plan would in fact reduce pollution because it appeared that even in the absence of the plan the future model cars would have met the same pollution levels anyway. Moreover, allowing GM to avoid a recall would destroy the incentive that the expense involved provides to build durable emission control systems that will last throughout a car's lifetime. NRDC and the Center for Auto Safety brought suit to block the GM-EPA agreement. In 1984, the court of appeals ruled in our favor, holding that the Clean Air Act requires the recall of offending vehicles. The settlement instituting the methanol bus program grew out of eighteen months of negotiations following that decision.

NRDC was willing to settle the case with the methanol bus program because the time consumed in litigation had diminished the effectiveness of a recall, since very few of the 1979 cars would likely be reached now. Instead, NRDC opted for the methanol program, which will accomplish some concrete environmental results and, by requiring a substantial expenditure from GM, will maintain the incentive for auto emission control durability. But now that the legal issue over recall is resolved, we say "never again." NRDC will not support remedies for future auto emissions violations other than recall.

Engine Modifications to Meet Future Diesel Standards

- Fuel injection
- Electronic engine controls
- Combustion chamber modifications
- Air handling characteristics
- Reduced oil consumption
- Turbocompounding
- → Reducing heat rejection

Thomas Baines

Fuel Injection

- Higher injection pressures decrease solid carbon through improved spray quality
- Unit injectors
  - Allow for very high injection pressures
    - Typical current pressures under 10,000 psi
    - Up to 16,000 psi achievable with pump and line systems
    - Up to 30,000 psi achievable with unit injectors (most will operate at 20-25,000 psi)

- Unit injectors (cont'd)
  - Better control over injection timing and profile through electronic control
  - Not generally considered for smaller engines
  - Some manufacturers claim there is little or no benefit from unit injectors

Fuel Injection (cont'd)

- Reducing injector nozzle sac and orifice volumes
  - Reduced SOF by reducing unburned HC
  - Some designs being implemented in 1987-1988 MY

Electronic Engine Controls

- Ability to optimize operating parameters over entire speed/load map
- Most manufacturers feel electronic control holds much promise
- Detroit Diesel already using DDEC system, others close behind

Combustion Chamber Modifications

- Optimizing air swirl for better mixing
  - Re-entrant bowl - promising if durability issues can be resolved
  - Intake manifold modifications
- Eliminating dead space to eliminate unburned HC
  - Reducing top ring land clearance
  - Eliminating head/valve pocket

Air Handling Characteristics

- Turbocharging
  - Using exhaust heat energy to compress intake air
  - Higher charge pressures reduce particulate
  - Approximately 90 percent of current engines turbocharged

Air Handling (cont'd)

- Aftercooling
  - Using heat exchanger to cool compressed intake air
  - Cooler charge reduces NOx
  - Approximately 70 percent of current engines use aftercooling
  - Major trend from Water Jacket to Air to Air

Air Handling (cont'd)

- Much turbocharging and aftercooling already in use
- Emphasis now on optimizing the system
- Some naturally aspirated engines being dropped

Reduced Oil Consumption

- Up to 10 percent of particulate from lubricating oil
- Improved piston ring design lowers oil consumption, but durability problems arise
- Advanced reduced oil consumption technology still in the lab shows much promise
- Some current engine designs already include good oil control

Turbocompounding

- Extracting exhaust heat energy and routing it into drivetrain
- Increase power output at same particulate output thus reducing g/BHP-hr
- Fairly expensive and would only be expected on large engines
- A longer term technology

Reducing Heat Rejection

- Reducing heat rejection allows for higher peak temperatures and more efficient burning of fuel
- Primarily achieved through ceramics
- Opinions vary greatly on potential benefits of ceramics
- A longer term technology

Conclusions

- Engine out reductions are a high priority for the manufacturers
- Non-trap compliance with 1991 standards on some engine lines is a possibility

Diesel Particulate Control:
Emerging Control Technologies to Address A Serious Pollution Problem

Presented by

Bruce I. Bertelsen
Executive Director
Manufacturers of Emission Controls Association

at the

Diesel Particulate Control/Alternative Fuels
Symposium
January 27-28, 1987
Chicago, Illinois

I. Diesel Particulate from Motor Vehicles Pose a Serious Threat to the Public Health and Welfare

Diesel particulates are extremely small, can be lodged deep in the most sensitive regions of the lung, and are suspected of contributing to or aggravating chronic lung diseases such as asthma, bronchitis, or emphysema. Moreover, up to 10,000 different chemicals, some of them known to cause cancer in animals and suspected by many health experts as causing cancer in humans, are absorbed with the diesel particulate and deposited deep in the lungs.

Diesel particulates, because of their size and composition, can greatly impair visibility. Studies indicate that diesel-powered vehicles may be responsible for significantly reducing visibility in major urban areas.

In addition, these particles soil public buildings and private residences, and contribute to structural damage by corrosion or erosion. Diesel exhaust also gives off a pungent and offensive odor.

Diesel trucks, buses and cars together are a significant and growing source of particulate emissions. Such vehicles emit 30 to 70 times more soot know as "particulate matter" than gasoline vehicles equipped with catalytic converters. Diesel engines currently power the majority of large trucks and buses, and by the late 1990's virtually all of the new large trucks and buses will be diesel powered. EPA predicts that unless controlled diesel particulates from motor vehicles will more than double current levels by 1995.

Diesel particulate emissions from motor vehicles are particularly troublesome because they are emitted directly into the breathing zone where we work and recreate.

II. Congress, EPA and California Responded to the Risks Posed by Diesel Particulate

Congress recognized the risks posed by diesel particulate and as part of the 1977 Clean Air Act Amendments established specific, technology-forcing requirements for controlling these emissions. The U.S. Environmental Protection Agency) (EPA) in 1980 established particulate standards for automobiles and light trucks. In 1985, after nearly five years of unfortunate delays, EPA established particulate standards for heavy trucks and buses. California, concerned that EPA standards would not adequately protect its citizens, adopted its own set of standards for passenger cars and light trucks.

Table I below summarizes the diesel particulate standards currently in effect.

TABLE I

PASSENGER CARS	PARTICULATE
1986 Federal	0.6 gpm
1986 California	0.2
1987 Federal	0.2
1989 California	0.08
LIGHT TRUCKS (under 8,500 lbs GVWR)	
1986 Federal	0.6 gpm
1986 California	0.2
1987 Federal	0.26
1989 California	0.08
HEAVY DUTY TRUCKS (8,500 lbs GVWR or over)	
1988 Federal & California	.6 g/BHP-hr.
1991 Federal & California	.25
1994 Federal & California	.1
URBAN BUSES	
1988 Federal & California	.6 g/BHP-hr.
1991 Federal & California	.1

The progress made in developing diesel particulate emission control since EPA first established standards for automobiles in 1980 has been dramatic. The remainder of this presentation will describe the advanced control technologies being developed and used in commercial application, and discuss the status of applying those technologies to the various catagories of motor vehicles.

An important factor to keep in mind in assessing the progress in developing and applying this technology is that this progress simply would not have occurred absent the presence of technology-forcing standards. Particulate emission control is a classic economic externality for the motor vehicle industry. Without a regulatory incentive, it is unlikely that sufficient pressure would be brought to bear on industry to aggressively pursue development of needed control systems.

III. Diesel Particulate Trap Oxidizers Offer A Technological Solution to Controlling Diesel Particulates

Manufacturers have had, and will continue to have, success in reducing particulate emissions from motor vehicles through vehicle and engine modifications. Since particulate emissions are roughly proportional to the amount of work done by the engine, the total particulate emitted can be reduced by reducing the amount of energy required to drive the vehicle. Therefore, such things as reducing vehicle size and weight, and changes in aerodynamic design have a positive effect in reducing diesel particulate emissions. Changes in engine design features such as combustion chamber design, fuel injection timing, fuel injection rate, and fuel spray pattern can also reduce particulate emissions. Even with such modifications, however, particulate emission levels remain high.

In order to achieve low levels of particulate emissions, manufacturers have turned to aftertreatment devices, that is, devices added to clean up the exhaust after it leaves the engine. The most promising of these aftertreatment devices is the trap oxidizer control system. Trap oxidizers systems have demonstrated particulate control efficiencies in some instances of over 90 percent.

A. Trap Oxidizers - How They Work

The trap oxidizer system consists of a filter positioned in the exhaust system designed to collect a significant fraction of the particulate emissions while allowing the exhaust gases to pass through the system. Since the volume of particulate matter emitted is sufficient to fill up and plug a reasonably sized filter over time, some means of disposing of this trapped particulate must be provided. The most promising means of disposal is to burn or oxidize the particulates in the trap, thus regenerating, or cleansing, the filter.

A complete trap oxidizer system consists of three components, the filter itself, the regeneration system and the controls which bring about regeneration.

1. Filter Material

A number of filter materials have been tested, including a monolithic ceramic trap, wire mesh, foam, mat-like ceramic fibers, and woven silica fiber coils. Collection efficiencies of these filters range from 50 percent to over 90 percent.

The ceramic cellular monolith filter is similar in construction to monolith catalyst supports used in gasoline engines. It is modified by blocking alternate channels in a checkerboard fashion on the entrance face. The opposite or exit face is similarly blocked, but one cell removed so that the gas cannot flow directly through a given channel. The entering exhaust gas is thus forced through porous walls to exit through an adjacent cell. The ceramic walls forming the cells serve as the filter medium.

The wire mesh trap oxidizer filter design is composed of knitted stainless steel mesh to which a high surface area alumina supported precious metal catalyst coating is applied. The presence of a catalyst in addition to oxidizing gaseous HC and CO facilitates the regeneration of the filter by catalyzing the oxidation of the collected material.

Another filter type is composed of sintered mullite fibers and silica alumina clay in a nearly 80% porous body. It is formed in a honeycomb configuration with plain and corrugated sheets joined together. Alternate cells are plugged similar to the ceramic wall flow design described above to form a filter element.

Silica carbide fibers can be adapted to be a filter in a densely packed tube form. Using radial flow from the outside to the inside, the particles are trapped in the body of the tube as well as on the outside surface.

Yet another trap oxidizer scheme being developed in Europe and specifically designed for heavy duty applications consists of treated silica fiber yarn woven in a number of porous metal tubes. The exhaust gas flows into a container through the walls of these "candles" and exits through the center of the tubes depositing its particulate content on the yarn.

Finally, ceramic foams such as those used as filters in the processing of metals are being examined as filter material for trap oxidizers.

2. Regeneration

The exhaust temperature of diesels is not always sufficient to bring about regeneration in the trap. A number of systems are being developed to bring about regeneration of traps. Some of these methods include:

- Throttling the air intake to one or more of the cylinders thereby increasing the HC and CO concentration in the exhaust.

- Using a catalyst coated trap. The application of a base or precious metal coating applied to the surface of the filter reduces the ignition temperature necessary for thermal oxidation.

- Using metallic fuel additives to reduce the temperature required for ignition of the accumulated material has been successfully demonstrated;

- Throttling the exhaust gas downstream of the trap. This method consists of a butterfly valve with a small orifice in it. Manually operated, the valve restricts the flow adding back pressure to the engine thereby causing the temperature of the exhaust gas to rise. Special controls of fuel input to the engine are also made at time of regeneration; and

- o Using burners or heaters to heat the incoming exhaust gas to a temperature sufficient to ignite the particulate.
- o With two cycle engines frequently found in transit buses a concept of bleeding predetermined amounts of scavenger air has shown very encouraging regeneration results.

The diversity in filter materials and regeneration systems being developed and employed illustrates the breadth of commitment to develop technological solutions. It also suggests that vehicle manufacturers will have choices available in selecting the control system that can best be applied for their particular vehicles and engines.

An alternative to trap oxidizers being evaluated by several diesel engine manufacturers is the conventional catalytic convertor similar to that found in today's gasoline-powered engines. The catalytic converter has been found useful for applications where a small amount of particulate reduction is required to meet standards. The catalyst oxidizes the soluble organic fraction of the particulate and does not actually perform as a trap or filter.

B. Affects of Trap Oxidizers on Engine and Vehicle Performance

The engineering goal of optimizing a trap oxidizer system to a particular application is that any adverse affects from its presence on vehicles and engine performance be eliminated or minimized to acceptable levels. Work to date with trap oxidizer development suggests these goals should be attainable. Several specific affects are discussed below:

1. NOx, Hydrocarbons, and Carbon Monoxide Emissions -

Non-catalyzed traps appear to have little or no affect on NOx or CO emissions, but a trap using a monolith wall flow ceramic filter did demonstrate the capability of reducing HC emissions by as much as 30 percent. Experience with the catalyzed wire mesh traps indicates that HC and CO emissions have been reduced to a considerable degree (in the range of 60-90 percent) with no adverse impact on NOx emissions.

2. Unregulated pollutants -

Though difficult to quantify, one manufacturer has found that ceramic traps significantly reduced aromatics, and also reduce SO_4 and noise. The experience with a catalyzed wire mesh trap indicates that there is a virtually complete reduction in odor and in the organic particulate fractions of the particulate, but some increase in sulfate emissions. Companies utilizing catalysts to provide regeneration for their traps are modifying catalyst formations to reduce any sulfates emitted to an acceptable level.

Reducing the sulfur content of gasoline -- (as has been done in parts of California) -- in addition to reducing pollution and engine wear, would help eliminate any problem with sulfate emissions from catalyzed traps. The U.S. EPA is currently considering a requirement for low sulfur fuel.

Trap systems which replace mufflers in retrofit applications have been shown equal sound attenuation to a stock muffler.

3. Fuel economy

A slight fuel economy penalty has been experienced with trap oxidizer technology which is attributable to the back pressure of the system. Some forms of regeneration involve the use of fuel, and to the extent those methods are used, there will be additional consumption of fuel. It is expected that the systems can be optimized to minimize, or in some cases possibly eliminate, any noticable fuel economy penalty.

4. Engine Wear and Vehicle Maintenance --

Trap systems do not appear to cause any engine wear or affect vehicle maintenance. Concerning maintenance of the trap system itself, manufacturers are designing systems to minimize maintenance requirements.

5. Vehicle acceleration and driveability --

Various trap oxidizers have been or likely can be designed so that driveability should not be affected, or at least can be minimized most notably by limiting back pressure.

6. Safety --

Safety is a paramount consideration in developing a trap system. In establishing the particulate standards, EPA expressed its belief that safe systems could be developed. Trap system manufacturers likewise are confident that safe systems can be developed.

C. Status of Trap Oxidizer Development

1. Light Duty Vehicles

Quite understandably the greatest advances in trap oxidizer technology have ocurred in light-duty vehicle application. Trap equipped passenger cars are now being sold by Daimler Benz (Mercedes). Mercedes first offered trap equipped vehicles in 1985 in several western states including California. A measure of the success of Mercedes' program is that for the 1987 model year, all but the Model 190 diesel powered vehicles are trap-equipped. Other passenger car manufacturers have met EPA's 0.2 gpm particulate standard without traps.

No light duty truck manufacturer currently markets trap-equipped vehicles. Nevertheless a number of promising systems are being developed.

Several years ago General Motors Corporation conducted a cross-country test with a fleet of trap-equipped vehicles. While the test program revealed a number of engineering challenges to be addressed, the overall results were encouraging.

Mitsubishi Motor Corporation reported at last year's Society of Automotive Engineers International Congress on tests of a trap oxidizer system consisting of a ceramic foam filter coated with a catalyst for regeneration, a back-up regeneration device (which senses particulate loading and increases exhaust temperature to cause incineration by catalytic reaction), and an emergency regeneration system which alerts the driver by means of a warning lamp to activate the regeneration device with a switch in the vehicle compartment. The system also included an odor reducing catalyst.

Two light-duty trucks powered with 2.3 liter turbocharged diesel engines were durability tested for 50,000 miles on the AMA cycle with the Mitsubishi system. Both vehicles completed 50,000 miles while maintaining tailpipe particulate levels of about 0.15 grams per mile. Mitsubishi reported during the durability testing that it was unnecessary to operate the manual regeneration device on either vehicle. Mitsubishi concluded that the catalyst coated trap filter system while not completely satisfying all the parameters of trap efficiency, cost, fuel economy, vehicle performance, practicability, reliability, and safety, did satisfy many of these demands and overall was an acceptable system.

2. Heavy Duty Vehicles

With EPA's and California's heavy-duty particulate standards now in place, engine manufacturers, trap manufacturers and others have turned their attention to the heavy duty application of trap oxidizers. Although EPA's standards have been in effect for less less than two years, the progress made is extremely encouraging.

Engine manufacturers throughout the world are subjecting prototype trap systems to a full range of testing. In addition, devices have been or are being evaluated by other parties interested in diesel particulate control, including: The Ontario Research Foundation; Southwest Research Institute; Michigan Tech University; Ricardo Consulting; the National Coal Board (England); and FEV (Aachen, West Germany). Of particular note, the Engine Manufacturers Association is sponsoring a program by an independent contractor to develop and evaluate a generic trap system.

One of the early successes of heavy duty trap application was a Daimler Benz trap-equipped bus which operated for 100,000 miles. Both Daimler Benz and Volvo White advised EPA during its standard setting process that trap equipped trucks and buses should be available in the early 1990's.

Heavy duty application of trap oxidizer presents special engineering challenges. While the basic technology to ensure a high trap collection efficiency has been established, the durability of a trap system in heavy-duty application--particularly in light of the longer useful life requirements, rugged use, volume of particulate emitted, and higher exhaust temperatures -- needs to be demonstrated.

Given the tremendous progress realized to date and the considerable combined research and development efforts of equipment and engine manufacturers, the prospects for addressing the remaining engineering challenges and having trap-equipped heavy duty vehicles in the early 1990's is excellent.

3. Retrofit Applications

Heavy duty vehicles meeting EPA's particulate standards will have greatly reduced particulate emissions. However, the EPA 0.1 g/BHP-hr. particulate standard for buses does not take effect until 1991 and for trucks not until 1994. We will be well into the next century before the fleet of clean burning diesel vehicles turns over completely.

Particulate emissions from transit buses in urban areas are of particular concern. Indeed, diesel pollution from buses is clearly the most talked about motor vehicle pollution problem.

Buses have a life span of up to 20 years. As a result, many localities are exploring the possibility of retrofitting buses with diesel particulate controls.

Trap manufacturers and others have separate development programs targeted for trap retrofit applications. Demonstration projects have been or are underway in the Netherlands, Great Britain, Munich, Athens, California, Philadelphia, and Tucson. A number of other demonstration projects are being planned. Two of these demonstration projects illustrate the significant progress and encouraging results that have been achieved.

The first program is in Athens, Greece. The City of Athens has one of the more serious air quality problems in the world. Diesel exhaust emissions are the major contributor. Two Athens' city public transit company buses have been equippped with trap oxidizer systems. The system is a ceramic wall flow filter with regeneration by means of exhaust throttling. The buses operate under real conditions on Athens' urban bus routes and have successfully operated for two years. In the near future, the program will expand to 25 buses.

The second program is taking place in Philadelphia. The Southeastern Pennsylvania Transit Authority (SEPTA) retrofitted a 6-V71 diesel engine-powered transit bus with a wire mesh catalyzed trap oxidizer. The bus has accumulated well over 40,000 miles in 20 months of revenue service.

Video recordings and visual inspections indicate that the bus had totally invisible exhaust under all revenue service operating conditions. SEPTA has reported no maintenance, performance, fuel or oil consumption problems and it has found that the system has gone largely unnoticed by the various drivers who have operated the bus. SEPTA reported the trap also appeared effective in controlling odor. SEPTA will continue to evaluate the trap's performance in order to identify capital and operating costs of such a system vis-a-vis using alternative fuels and other emerging methods for controlling diesel particulates.

CONCLUSION

- Diesel particulate emissions from motor vehicles pose a serious health and welfare threat, but diesel particulate trap oxidizers represent a technology that can greatly reduce particulate emissions from motor vehicles.

- Substantial progress has been made in developing and applying trap oxidizer technology since EPA first adopted particulate standards in 1980. In 1987 trap equipped automobiles are being marketed nationwide.

- Trap oxidizer applications to heavy duty vehicle offers special engineering challenges. Engine manufacturers, trap manufacturers and others, however, are engaged in worldwide development efforts to refine trap oxidizer technology for heavy duty application and the prospects for meeting those challenges and having trap-equipped heavy duty vehicles in the 1990's appear excellent.

- The significant progress in developing trap oxidizer technology is a direct result of technology forcing standards established by the U.S. Environmental Protection Agency and the State of California. If progress is to continue, it is essential that these technology-forcing standards remain in effect.

- Existing heavy duty diesel powered vehicles, particularly buses operated in urban areas, pose a special problem to the air quality of our nation's cities. A number of development and demonstration projects involving retrofit trap application to transit buses are underway and the results to date have been extremely encouraging. Retrofit application of diesel particulate traps offers a unique opportunity for local governments, engine manufacturers, and device manufacturers, to work together to find solutions to this problem.

Status of Exhaust Aftertreatment Projects

- Overview of Projects
    - → EPA
    - Heavy Duty Engine Manufacturers
    - Equipment Supplier Industry
    - Research Institute
- Status Summary
    - Trap Oxidizer Concepts
    - Trap Oxidizer Regeneration
    - Oxidizing Catalysts

Thomas Baines

EPA Exhaust Aftertreatment Projects

1. Concepts development
    - Performed on light duty diesels
    - Most promising will be applied to heavy duty engines
    - Current work
        - Face heated ceramic wall-flow monolith
        - Electrically conductive substrate (Fogarty)

2. Heavy Duty Technology Evaluation

   - Caterpillar 3208 with Mercedes-Benz LD Traps
   - Low cost wire mesh
   - Catalytic converter
   - Johnson Matthey

Heavy Duty Engine Manufacturers

- Manufacturers main emphasis is on engine-out particulate reductions
- All manufacturers also have a trap program

- Mostly proprietary information
- Some work is still in the lab but there are some vehicle demonstrations
- Main concepts:
  - Ceramic monolith
  - Catalyzed wire mesh
  - Ceramic fiber coil

Equipment Supplier Industry Projects

- Corning support role
  - Supply Daimler-Benz LDD Traps
  - 40 buses in Europe
  - Product being tested by all HDD manufacturers

- Johnson Matthey
  - Light duty diesel research
  - Apply promising concepts to HD catalyst formulations trapping media
  - Field Durability Trials
    - SEPTA (Philadelphia)
    - (Tucson)
  - Product being tested by some HDD manufacturers

- Muffler Manufacturers
  - Donaldson, Nelson, [redacted] ARVIN
  - Traps may replace mufflers
  - They may produce a complete system
  - Tread towards distributing costs

Research Institute Projects

1. Southwest Research Institute
   - EPA Trap-equipped bus
   - CARB bus engine work
   - Internal Funding
     - Silica foam
     - Silicon carbide foam
   - Consortium Multi-client
     - Fundamentals of regeneration and control

2. Ontario Research Foundation
   - EMA funded joint research
     - Burner-assisted regeneration
     - Ceramic wall flow monolith
   - Ontario Government project
     - Demonstrate trap on a local bus

Trap Oxidizer Concepts

1. Ceramic monolith
   - Most prominent and likely trapping concept
   - High efficiency (up to 90 percent)
   - Much promise if durability problems (melting/cracking) can be solved through better control of regeneration and/or ceramics with better thermal properties

2. Catalyzed wire mesh

   - Low trapping efficiency (40-60 percent)
   - High reduction of SOF
   - Increased sulfates

3. Ceramic fiber coil trap
   - Developed by Daimler-Benz
   - Good durability
   - Medium trapping efficiency (60-80 percent)
   - Hard to regenerate

Trap Oxidizer Regeneration

1. Active Regeneration - May be a prefered approach for HD application

    A. Fuel burner system

    - Generally involves exhaust bypass
    - Problems with maintaining proper oxygen concentration and good heat distribution
    - Some safety concern (accident while burner is on)

B. Electric Heater System

- Face heater or (more recently) use of conductive substrate
- Good control of heat distribution
- Can involve large electricity demand

2. Passive Regeneration

- Exhaust temperatures generally too low for successful passive regeneration
- Catalysts which lower particulate regeneration temperatures are primary path for passive regeneration

- Catalysts applications
  - Coating on traps
  - Fuel additives (pre or post engine)
    - * Problems with additives eventually plugging trap
    - * Safety concerns include emissions of catalyst and handling of leftover catalyst when vehicle is scrapped

- Fuel sulfur a problem for most catalysts (sulfate formation)
- Unless sulfur is reduced or more selective catalysts can be found it is unlikely that their use as a passive regeneration method will be widespread in the future

Oxidizing Catalysts

- Oxidizes SOF (80-90 percent efficient)
- 15 to 35 percent reduction in total PM
- If engine levels are close to standard this may be a feasable approach
- Fuel sulfur a problem (sulfate formation for many catalyst formulations)

Fuel Quality Control Issues

- Advantages:
  - Potentially significant particulate emission reductions
  - SO_2, secondary particulate reductions
  - Possible engine wear reduction
  - Potentially lower engine price increases due to less costly exhaust treatment devices

- Disadvantages:
  - Fuel price increase
  - Fuel economy decrease (due to aromatics reduction)

Timothy Sprik

Aromatic Content

- ASTM Limit: None
- Current Level: 29% by volume
- Levels expected to increase as cheaper crudes are used

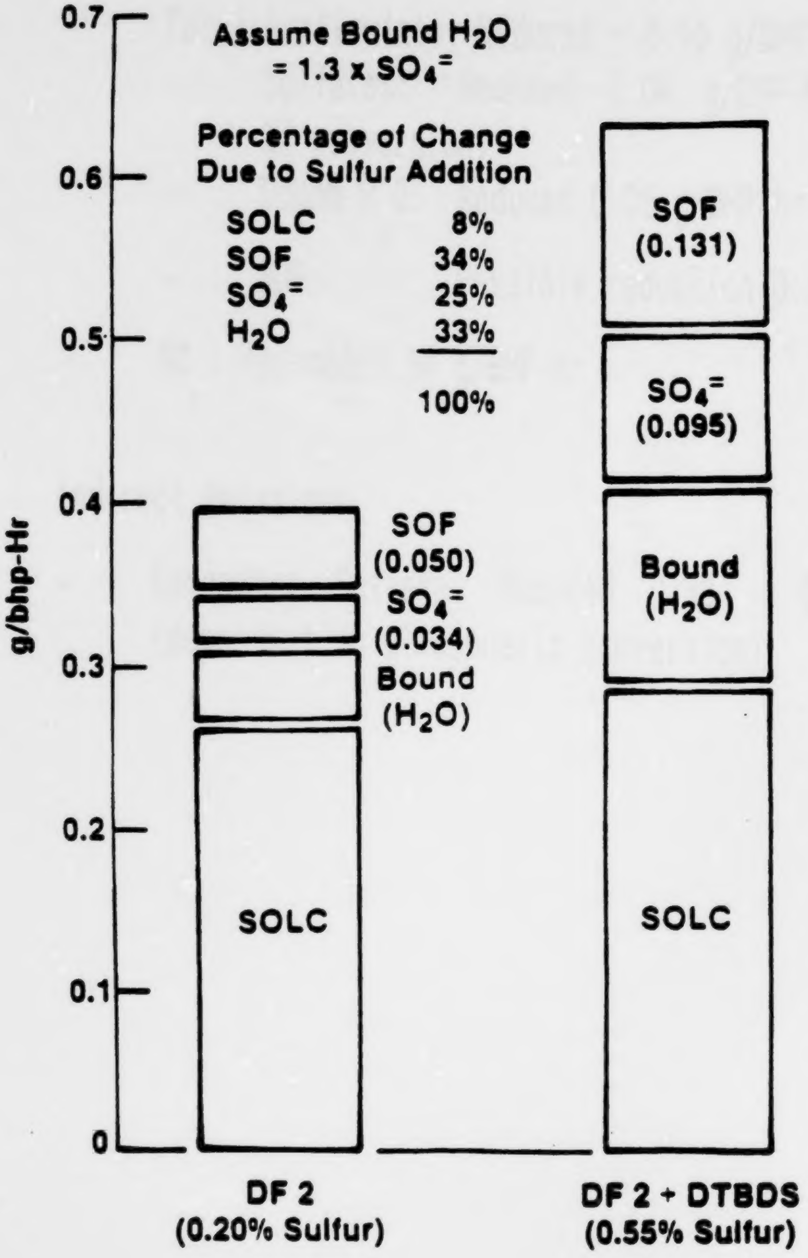
Sulfur Content

- ASTM Limit: 0.50 wt. %
- Current Level: 0.27 wt. %
- South Coast Air Basin Standard: 0.05 wt. %
- Survey data shows sulfur content is increasing

Effect of Sulfur on Engine-Out Emissions

- Particulates
  - Sulfates: Typically 2-6% of sulfur in the fuel is converted
  - Bound H_2O: Roughly 1.3 x sulfate at 50% humidity
  - SOF: Possibly a weak correlation
- Sulfur Dioxide (SO_2)
  - Typically 94-98% of fuel sulfur
  - Between 30 and 70% of SO_2 is converted to sulfate in the atmosphere

EFFECT OF FUEL SULFUR INCREASE ON TOTAL PARTICULATES AND INDIVIDUAL FRACTIONS AT 1400 RPM/112 BHP



(Presentation to EPA "Fuel Composition Effects on Diesel Particulate Emissions", Chevron Research Company, 8/21/84)

Effect of Change from 0.27 % to 0.05% Fuel Sulfur on Emissions

- Direct Emissions
  - Total Particulate: Reduced ~ 0.10 g/BHP-hr
    - Sulfates: Reduced 0.04 g/BHP-hr (based on 3% conversion)
    - Bound H_2O: Reduced 0.05 g/BHP-hr
    - SOF: Possible reduction 0.01 g/BHP-hr
  - SO_2: Reduced 0.84 g/BHP-hr
- Indirect Emissions
  - Secondary Sulfate: Reduced 0.38 - 0.88 g/BHP-hr (dependant on atmospheric conversion)

Effect of Aromatics on Engine-Out Emissions

- Particulates
  - Fuel aromatics correlated with carbonaceous portion and soluble organic fraction (SOF) of particulates
- Gaseous Emissions
  - Can be correlated with HC and NOx emissions
  - Effect uncertain and probably highly engine specific

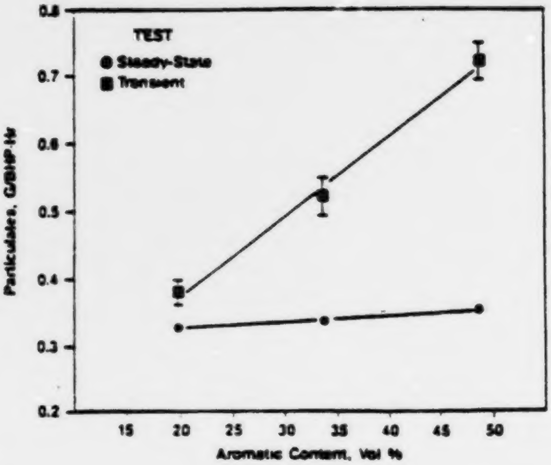


Figure 18

AROMATIC CONTENT EFFECT
ON PARTICULATES

(SAE #852073, Barry et alia, 1985)

Effect of Change from 29% to 20% Aromatics on Emissions

- Particulates
  - Carbonaceous: Reduction of about 0.10 g/BHP-hr on existing engines
  - SOF: Possible slight reduction (< 0.05 g/BHP-hr)
- Gaseous Emissions
  - Possible reductions in HC, NOx

Effect of Fuel Sulfur on Exhaust Aftertreatment Devices

- Ceramic Monolith
  - Sulfates can lead to problems by plugging monolith walls
- Catalyzed Wire Mesh
  - Catalyzed traps increase conversion of SO_2 to sulfate particulates
- Oxidizing Catalysts
  - Significant increase in sulfate formation
  - Infeasible unless highly selective catalyst is found or fuel sulfur is reduced

Cost of Sulfur Reduction to 0.05% Through Hydrodesulfurization

- **CARB**: 2.6-7.4 ¢/gal. (survey results)
- **ERC/Sobotka**: 1.2 ¢/gal. (refinery modelling)
  - achieved through segregation of diesel and distillate burner fuel
  - ~ 8 vol % decrease in aromatics would result from desulfurization
- Bonner & Moore Modelling (Sponsored by EPA):
  - quality of off-highway distillate fuel maintained
  - various degrees of segregation considered
  - preliminary results expected in Spring 1987

Cost of Aromatics Reduction through Hydrotreating

- Method: Severe hydrotreating, similar to hydrodesulfurizing
- CARB: 5.7 ¢/gal. (from 33 to 10 vol %)
- ERC/Sobotka: Reduction to 20 vol % achieved as side effect of desulfurization via blending and product segregation (Further reduction to 17 vol % acheived at 0.4¢/gal)
- Bonner & Moore: Currently investigating cost of reducing aromatics to 20 vol %

Engine Durability Effects of Fuel Sulfur

- Increased sulfur levels in fuel cause corrosive wear problems
- ERC Report claimed a 30% reduction in wear rates resulting from desulfurization based on locomotive test data
- Comments from manufacturers claim reduction in wear will be minimal
- Testing by Daimler-Benz hows fuel sulfur has minimal effect on wear at normal operating temperatures
- Southwest Research Institute currently is evaluating lube oil analysis from Southern California fleets

EPA Action

- EPA contractor report by ERC/Sobotka has been released for public comment
- Meetings with representatives of the oil industry and engine manufacturers to coordinate further modelling work and investigation have taken place
- EPA currently developing comprehensive environmental and economic impact study to be released in the near future

THE ENVIRONMENTAL PROTECTION AGENCY VIEW OF METHANOL AS A TRANSIT BUS FUEL

Presented at the Headway '85 Transit Conference
in Kansas City, Missouri on November 4, 1985

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Environmental Protection Agency (EPA) interest in transit buses has increased significantly in the last few years. Concerns over existing diesel bus pollution and enthusiasm over the potential of methanol to alleviate these concerns have both contributed to this increased interest. This paper will give an overview of the transit bus issue from an EPA perspective, summarizing our current outlook on diesel buses, discussing methanol as a general motor vehicle fuel, and focusing on the benefits of methanol as a future transit bus fuel.

A Reassessment of Diesel Bus Pollution

Historically, transit buses have not been considered to be a significant environmental problem. In any urban area, the number of transit buses is only a minute fraction of the total number of motor vehicles. Powered by diesel engines, which inherently produce low levels of hydrocarbon (HC) and carbon monoxide (CO) emissions, total mass emissions of most pollutants from transit buses are dwarfed by aggregate emissions from passenger vehicles, large trucks, and stationary sources such as power plants and factories. In addition, from a technical perspective, there has not been a promising bus or truck alternative to the diesel cycle engine operated on diesel fuel. Accordingly, EPA regulation of heavy-duty trucks and buses has lagged behind that of passenger cars and light trucks, and current EPA standards require only token control measures on new heavy-duty diesel engines.

A number of developments have forced EPA to reexamine the diesel bus issue. As EPA has reduced emissions from other sources (for example, new passenger car HC and CO emissions have been reduced by over 90 percent in the last fifteen years), bus emissions have become proportionally more important. Public health concerns with diesel particulate matter (PM) and oxides of nitrogen (NOx) emissions have increased, the former because of evidence that it contains carcinogenic compounds and the latter because air quality projections show that certain areas of the country will exceed EPA's ambient standard during the 1990s, and both of these pollutants are emitted in relatively large amounts by diesel engines. As our ability to analyze motor vehicle emission impacts has become more sophisticated, we have determined that public exposure to transit bus pollution is much higher than to many other pollution sources, on a per unit mass basis: buses are operated exclusively in urban areas, typically over the busiest roadway corridors with maximum population exposure, the pollution is emitted at ground level directly into the human breathing zone, and EPA and local environmental officials receive a high frequency of complaints about bus pollution and odor. Finally, recent EPA testing has indicated that actual diesel bus emissions of certain pollutants, such as CO and PM, are much higher than previously thought.

Table 1 lists the current and future emission standards which have been established for new engines to be utilized in transit buses, as well as ranges for the emissions of current technology engines. It can be seen that current diesel bus engines are comfortably below the current HC and CO standards of 1.3 and 15.5 grams per brake horsepower-hour (g/bhp-hr), respectively, and that these standards are not expected to change in the future. The situation with NOx and PM standards is in a state of flux, however. We currently have a NOx standard of 10.7 g/bhp-hr, which represents very little control, if any, and no PM standard (there is a smoke standard which constrains PM emissions somewhat). On March 15, 1985, EPA promulgated new rules which will, for the first time, require meaningful NOx and PM reductions from heavy-duty diesel truck and bus engines. Interim standards beginning in 1988 will require minor improvements on some engine models. By 1991, new diesel bus engines will be subject to a NOx standard of 5 g/bhp-hr, similar to a standard already in effect in California. This will require some type of engine modification on most new bus engines. Also beginning in 1991, new bus engines will have to meet a 0.1 g/bhp-hr PM standard. This is a very significant reduction in allowable PM emissions, and will likely require the application of trap oxidizers, exhaust aftertreatment devices which continuously filter and periodically oxidize PM.

The lower diesel bus emission standards in 1991 have certainly contributed to the interest of diesel engine manufacturers in alternative fuels. The application of trap oxidizers and NOx controls will undoubtedly raise the initial purchase price, and probably the fuel consumption as well, of transit bus engines. A second motivation is simply the realization that we will not have abundant supplies of cheap diesel fuel forever, and that an alternative fuel will ultimately be necessary.

Methanol: The Transportation Fuel of the Future

Whether examined from an energy, environmental, or economic standpoint, methanol is a very promising alternative motor vehicle fuel. Of course, the historical context for interest in methanol, and all alternative liquid fuels, involves the oil price shocks of the 1970s. American society had prospered on cheap and plentiful oil, and it was only after the OPEC oil embargo of 1973-74 that we realized that petroleum was a finite and valuable resource. Our vulnerability with respect to energy security was reinforced in 1979-80 when a relatively minor cutoff of crude oil from Iran caused major havoc with world oil prices. Prices rose from $3 per barrel in the early 1970s to nearly $40 per barrel in 1981. Oil import payments, which peaked at $80 billion in 1980, became a major drain on American capital, and contributed to a decline in our international trade balance.

Although the present world oil price and supply situation is much improved, with plentiful supplies and falling prices, we cannot afford to become overconfident. Domestic oil production, which has been constant for several years, is projected to decline in the late 1980s, as shown in Figure 1. The combination of lower domestic oil production and increased economic growth is expected to significantly increase our appetite for imported oil. In addition, world economic recovery and growth and falling crude production in other non-OPEC areas are expected to significantly increase world oil prices in the 1990s. It is expected that our oil import bill will exceed $100 billion per year by the early 1990s if a satisfactory liquid fuel substitute is not found. Figure 2 indicates that our cumulative international trade deficits are increasing at a high rate, due to record merchandise trade and current account deficits in 1984. Higher oil import bills in the 1990s can only worsen our trade difficulties. Since, as shown in Figure 3, approximately 60 percent of U.S. petroleum consumption is in the transportation sector, it is clear that the U.S. will ultimately require a liquid fuel alternative to petroleum which can be produced from domestic energy resources.

From an energy perspective methanol is an attractive alternative. It can be produced in very large volumes from a variety of domestic feedstocks such as natural gas, biomass, and, most importantly, all types of coal. Our huge domestic reserves of coal, evidenced in Table 2, will undoubtedly be a feedstock for alternative liquid fuels in the future. The production technology for coal-to-methanol plants is technologically proven as both the coal gasification and methanol synthesis processes are in use today. The fact that coal would go through a gasification step would permit any sulfur in the coal to be easily removed allowing the use of high-sulfur coal. As a liquid fuel, methanol would generally be compatible with existing vehicle and distribution systems. Finally, it has been known for decades that methanol is a very efficient, high-octane motor vehicle fuel. From an overall energy efficiency perspective, methanol would likely provide the maximum number of vehicle miles per ton of coal feedstock.

Methanol has always been considered to be a very clean-burning fuel; in fact, its low emissions, especially of nitrogen oxides, was a primary impetus for many of the initial methanol research projects of the early 1970s. Of course, we now have much more stringent passenger car emission standards, and sophisticated emission control technologies have been developed to control emissions from gasoline-fueled cars. Compared to gasoline-fueled vehicles, methanol vehicles would likely emit lower levels of reactive hydrocarbons, leading to a projected decrease in photochemical oxidant levels. Engine-out nitrogen oxide levels would also be lower, though whether vehicle emission levels would be lower would depend on the emission control system used (i.e., manufacturers might choose to use a lower cost catalyst).

The environmental benefits of methanol are most evident when considered as a substitute for diesel fuel. Diesel engines inherently emit high levels of particulate and nitrogen oxide emissions, and trucks and buses are major sources of these pollutants in many urban areas. Methanol engines tend to emit very low levels of both of these pollutants. Methanol substitution for diesel fuel would also reduce reactive hydrocarbon and sulfur dioxide emissions as well. From an environmental perspective, the use of methanol provides the opportunity for vehicle manufacturers and consumers to achieve the energy efficiency of a diesel engine but with exhaust emissions comparable to or better than the cleanest gasoline engine. Bus emissions will be discussed in more detail later in this paper.

Of course, fuel economics will be vital to the viability of any alternative liquid fuel. EPA has studied this issue extensively and concluded that methanol would be the most cost-effective liquid fuel, on a dollar per mile basis, of any of the candidate fuels which can be produced from coal. When methanol would be competitive with petroleum fuels is very dependent on world oil prices. Our studies indicate that methanol would be competitive with gasoline from $35 per barrel oil and competitive with diesel fuel when crude oil prices reach $45 per barrel. Even assuming that there will be no world oil supply disruptions, most forecasts are that world oil prices will rise above these levels in the 1990s.

There is a growing consensus that methanol is our most promising alternative transportation fuel. Both Ford and General Motors have active methanol vehicle development programs and various foreign manufacturers are also involved in the area. Many energy and chemical industry firms have studied the economic feasibility of coal-to-methanol production plants, though plans are presently on hold due to the large methanol surplus and falling world oil prices. Methanol vehicles are currently being evaluated by private and public sector fleet operators throughout the U.S., such as the Bank of America and the California Energy Commission.

Interest in methanol development has reached the highest levels of our federal government and both major political parties. The Administration has formed a Methanol Working Group composed of representatives of 15 different executive agencies and White House staffs. The primary purpose of the working group is to review regulatory requirements which might inhibit consumer use of methanol. Various pieces of proposed legislation have attracted bipartisan support in Congress including federal fleet demonstrations, explicit appropriations for methanol bus purchases, the establishment of a formal interagency commission on methanol, and changes in methanol fuel taxation. Given the interest by high-ranking members of both parties, it is expected that such proposals will continue to be considered.

Thus, with respect to environmental, energy, and economic considerations, we believe methanol is the most promising alternative transportation fuel. The conversion of our national vehicle fleet to pure methanol could eliminate our need for oil imports with concomitant benefits such as an improved balance of trade, insurance against the economic dislocations caused by another oil price shock, and increased national security. The redirection of the U.S. wealth now going for oil imports into domestic coal-to-methanol production could increase domestic economic growth and employment and would provide a needed market for high-sulfur coal. And, at the same time, the use of methanol in motor vehicles would improve urban air quality.

The Potential for Methanol as a Transit Bus Fuel

While we believe methanol has the potential to ultimately displace petroleum fuels in all motor vehicle applications, it is particularly attractive at the present time for use in transit buses. There are several reasons why methanol transit buses could be implemented much more easily than could a general fleet transition to methanol. First, because most transit authorities are public agencies, they should be sensitive to public complaints about the environmental problems of diesel buses and the benefits to be gained from operating methanol buses. Transit agencies typically receive operating subsidies from local units of government, and this provides a leverage point for citizens interested in reducing air pollution. Even more directly, since the federal government provides up to 80 percent of the funds used to purchase new urban buses, it could directly promote interest in methanol buses by providing financial inducements for technology transfer or by simply requiring that all federal monies be used for methanol bus purchases. Second, transit authorities have centralized fueling sites which could be modified to store and dispense methanol fairly easily. This means that a methanol bus implementation program would be largely immune from the distribution problems which would be associated with the widespread transition to a fuel like methanol, with its different chemical properties, requiring that scores of thousands of private service stations be capable of storing and dispensing it. Finally, because transit systems also have centralized maintenance facilities, there would be far fewer concerns over the proper maintenance and repair of a "new" or at least different engine technology. Thus, urban buses are probably the most appropriate vehicles to be initially fueled with methanol.

Several heavy-duty engine manufacturers are now involved in methanol research programs. Despite the fact that research into the use of methanol in diesel engines is a fairly recent phenomenon, manufacturers have already achieved considerable progress. Three manufacturers have developed methanol-fueled diesel-cycle bus engines: M.A.N., Mercedes-Benz, and General Motors. M.A.N.'s involvement in the German Alcohol Fuels Project led them to modify an existing 11.4-liter, six-cylinder, direct-injected, naturally-aspirated, four-stroke diesel engine for pure methanol combustion. The two key aspects of the modification were the addition of spark ignition and the functional separation of fuel injection and mixture formation through wall deposition of the methanol. M.A.N. is now developing a turbocharged version of this same methanol bus engine.

Mercedes-Benz has designed a 11.4-liter, six-cylinder, spark-ignited engine to operate on gaseous methanol, in order to take advantage of methanol's relatively low boiling point (permitting vaporization) and high heat of vaporization (increasing usable energy). The engine, adapted from a design originally intended for operation on natural gas and propane, features a fuel vaporizer which utilizes heat energy from engine cooling water.

General Motors has only recently become involved in methanol bus engine research. GM selected its 9.0-liter, six-cylinder, direct-injected, turbocharged, two-stroke diesel engine, used in most new U.S. transit buses, as its baseline engine. It was found to be surprisingly easy to autoignite pure methanol in the two-stroke engine at normal engine operating temperatures by controlling the exhaust gas scavenging process to produce the requisite in-cylinder conditions at the time of fuel injection. In effect, much of the exhaust gas is maintained in the cylinder thus providing sufficient temperatures for methanol ignition. Glow plugs were added to the engine for use in cold starting and light-load operation.

Each of these three manufacturers now has methanol buses in various demonstration programs throughout the world. Prototype methanol buses are now operating in revenue service in San Francisco (GM and M.A.N.), Berlin (M.A.N. and Mercedes), Auckland, New Zealand (M.A.N. and Mercedes), and Pretoria, South Africa (Mercedes). Each bus has had some problems, but none appear to be insurmountable. Both the engine manufacturers and the demonstration sponsors have been pleased with each of the programs.

The most critical ongoing demonstration program for U.S. policymakers, both because of the manufacturers involved and its accessibility, is the one in San Francisco sponsored by the California Energy Commission. Two GM and M.A.N. methanol buses, which went into service for the Golden Gate Bridge, Highway, and Transportation District in January and July of 1984, respectively, will be operated in normal revenue service until the end of 1985, at which time it is likely that additional funding will be sought to continue the demonstration. The program has been designed to provide important information with respect to operating cost, fuel and oil consumption, emissions, maintenance, driveability, durability, and consumer and driver reaction. Experience gained from this program will be very helpful in planning for more comprehensive demonstrations in the future. In general, the San Francisco demonstration has been very successful in proving the feasibility of methanol transit buses. The M.A.N. bus has been particularly impressive with very few maintenance problems and an energy efficiency equivalent to its diesel counterpart both in service and on track fuel economy tests. As of October 1985, the M.A.N. bus had accumulated 37,000 miles. The GM bus was beset with some problems early in the program, but is now running well and has accumulated 27,000 miles. The GM bus has not yet reached an energy efficiency equivalent to the diesel. Both of the buses have exhibited performance equivalent to diesel buses. For more detailed information on this program, the reader should consult Society of Automotive Engineers paper number 850216.

A second U.S. demonstration, sponsored by the Florida Department of Transportation and UMTA, is also ongoing. Its purpose is to determine the costs and benefits of retrofitting in-use GM 71-series diesel bus engines to methanol. Three engines have been converted in 1985 and will be put into service in Jacksonville, Florida for six months in early 1986. This program is more fully described in Society of Automotive Engineers paper number 841687.

Based on the promising results to date, additional demonstrations, involving larger numbers of buses and the active interest and participation of individual transit authorities, are being planned. Seattle Metro Transit has signed a contract to purchase 10 M.A.N. methanol buses,with delivery expected in late 1986. The Southern California Rapid Transit District is expected to solicit bids for 30 methanol buses in the near future. Officials in several other cities, such as New York and Denver, have also expressed interest.

It is becoming increasingly clear that environmental considerations comprise the primary driving force toward the use of methanol in transit buses. While interest in alternative fuels is generally a function of oil prices and availability, the enthusiasm for methanol buses has grown significantly in the last two years despite a world oil glut and falling oil prices. Our discussions with local environmental officials and individual transit authorities have indicated that there would be a high value associated with a transit bus fuel which was cleaner than diesel fuel. What would be the environmental implications of substituting methanol buses for diesel buses?

EPA has tested many diesel bus engines down through the years. Until very recently EPA has relied exclusively on engine dynamometer testing which simplifies the laboratory expense of characterizing an engine which may be used in a number of truck and bus chassis applications. In addition, an engine dynamometer can be smaller and cheaper than a chassis dynamometer. Data collected prior to the late 1970s was generated over steady-state engine testing which is not considered to be very representative of in-use transit bus operation. Much of the more recent data was generated over the EPA heavy-duty transient engine test procedure, which is used for official EPA certification purposes. This involves operating an engine over a test cycle that consists of engine speed and load transients which were designed to simulate intercity truck usage (truck operation was selected for the cycle design because trucks outnumber buses). The first column in Table 3 gives the average engine emissions data for three new diesel bus engines which EPA has tested over our certification transient engine test cycle.

Of course, the relevant information for air quality models is the grams per mile (g/mi) that a vehicle is emitting. Historically, EPA has typically used a "conversion factor" of between 3 and 4 to convert engine emissions in g/bhp-hr to vehicle or chassis emissions in g/mi. Recently, EPA has tested 7 diesel buses pulled directly from operating service and operated on a chassis dynamometer over emission test cycles designed to simulate transit bus operation. Three of these buses were GMC RTS II buses from the Houston bus fleet which were equipped with DDAD 6V-92TA diesel engines. Four GMC RTS II buses with DDAD 6V-71 diesel engines from the San Antonio transit authority were also tested. These buses had accumulated between 55,000 and 247,000 miles prior to testing. Two chassis test cycles were used, an EPA bus driving cycle and the central business district phase of the SAE Type II Fuel Consumption Test Procedure for buses. Both of these chassis cycles involve transient operation with low average speeds and high acceleration rates, and both cycles have yielded fuel economy values which correlate well with field data. The second column in Table 3 gives the average emission data for these 7 buses. It can be seen that multiplying the engine data by a conversion factor of 3 or 4 is pretty reliable for HC and NOx emissions, but that this methodology does not hold for CO and PM emissions. The CO and PM emissions for in-use diesel buses were much higher than predicted by the engine data. The discrepancies reflect some combination of engine aging and wear, maladjustment, or more realistic test cycles. In any case, EPA has concluded that previous projections of diesel bus emissions have been underestimates, and that chassis testing is necessary for accurate quantification of bus emissions.

Nevertheless, until recently there was no methanol bus chassis data, only methanol engine data. Table 4 compares the diesel bus engine emissions data from Table 3 with engine emissions data for the M.A.N. and GM methanol engines. All of these engines were new or nearly new. The M.A.N. methanol engine was tested by the Southwest Research Institute under contract to EPA. The engine was equipped with an oxidation catalytic converter and tested over the EPA transient engine test cycle. The GM methanol engine was tested by GM over the older EPA 13-mode steady-state engine cycle. It did not utilize a catalytic converter. As can be seen, CO and HC emissions were not reported by GM.

The engine data in Table 4 show clearly that methanol, because of the absence of carbon-carbon bonds and fuel impurities such as lead and sulfur, produces very low levels of PM. Besides being a critical environmental benefit in and of itself, the low particulate levels also permit the utilization of catalytic converters which, as shown by the M.A.N. data, reduce total organics and CO levels as well. The NOx data is mixed. While methanol is considered a low-NOx fuel because of its low flame temperature, the M.A.N. methanol engine actually emitted slightly more NOx than the diesel engines. On the other hand, the NOx emission level from the GM methanol engine is the lowest ever reported to EPA for a heavy-duty engine.

One of the most interesting issues with respect to methanol fuel is organic (or fuel-related) emissions. Organic emissions from diesel (and gasoline) vehicles are comprised almost exclusively of HC compounds (with small amounts of other compounds such as formaldehyde), and EPA regulates these with a single HC standard. Organic emissions from methanol combustion are typically 90 percent (or more) unburned methanol with the remaining fraction being primarily formaldehyde with low levels of HC. As the data in Table 4 show, methanol engines emit considerably lower HC emissions, much greater methanol emissions, and similar levels of formaldehyde compared to diesel engines. Even if overall mass organic emissions were similar, methanol is considered to be less photochemically reactive than most HC compounds. Thus, methanol substitution could reduce the photochemical reactivities of urban atmospheres, resulting in lower ozone levels. Preliminary computer modeling simulations have projected reduced reactivities, and EPA is now in the process of validating these results with smog chamber research.

Just this last summer EPA completed a comprehensive methanol chassis emission test program at Southwest Research Institute with the M.A.N. and GM methanol buses from the San Francisco demonstration program. This is the first such testing of methanol buses anywhere in the world and permits us to directly compare diesel and methanol bus emissions. This comparison is given in Table 5. The diesel bus data, involving 7 in-use GM buses with both 71-series and 92-series engines, are repeated from Table 3. All of these buses were operated over the EPA bus and SAE central business district test cycles. The M.A.N. methanol bus utilized a catalytic converter, while the GM methanol bus (and, of course, the diesel buses) did not. The chassis data in Table 5 generally confirm the engine data in Table 4. The methanol chassis emissions data are particularly impressive for PM and NOx, the two primary pollutants of concern from diesel buses. Both methanol buses yielded PM and NOx reductions compared to the diesel baseline, with the M.A.N. bus especially low on particulate and the GM methanol bus very low on NOx. The M.A.N. bus also emitted low levels of CO and organics as well, due to both an efficient combustion process and the presence of a catalytic converter. Of particular significance is that aldehyde emissions from the M.A.N. bus were lower than from the diesel buses. The GM methanol bus produced extremely high CO and organics emissions,with the very high methanol (i.e., unburned fuel) emissions an indication that there is still the need for considerable fundamental engine design work to be done with this engine. This should not be surprising since this is the very first methanol bus built by GM. The application of a catalyst would also lower CO and organics emissions (and likely PM as well, since most of the particulate is organic, formed by the combustion of small amounts of lubricating oil).

In summary, initial tests of methanol-fueled diesel engines and buses confirm theoretical expectations that the substitution of methanol for diesel fuel could provide significant emission benefits. PM emissions would be greatly reduced, and would likely be near zero for some engine designs. NOx emissions would be reduced by at least 50 percent. Methanol engines would likely be able to meet any future, more stringent, PM and NOx standards without requiring additional emission controls. Assuming the use of an exhaust catalyst, which EPA believes should be mandatory, methanol engines would also provide reactive HC reductions, with concomitant improvements in atmospheric ozone levels, and CO reductions as well. Present data indicate that catalysts would reduce aldehyde emissions to levels equivalent to or below those of current diesel engines. The only pollutant which would be increased would be unburned methanol although catalysts would reduce it to acceptable levels.

Of course, whether methanol buses become a realistic alternative is in large part dependent upon fuel costs. It is very difficult to project the future operating costs for methanol and diesel buses with a high degree of confidence. Prices for both fuels are currently depressed because of excess capacities, though it is unclear how long these surpluses will continue. Diesel fuel prices are particularly difficult to project given their dependence on world oil prices. Nevertheless, given the vital importance of fuel costs in the operation of a transit authority, it is important to have some idea of the relative operating economics of methanol and diesel fuels.

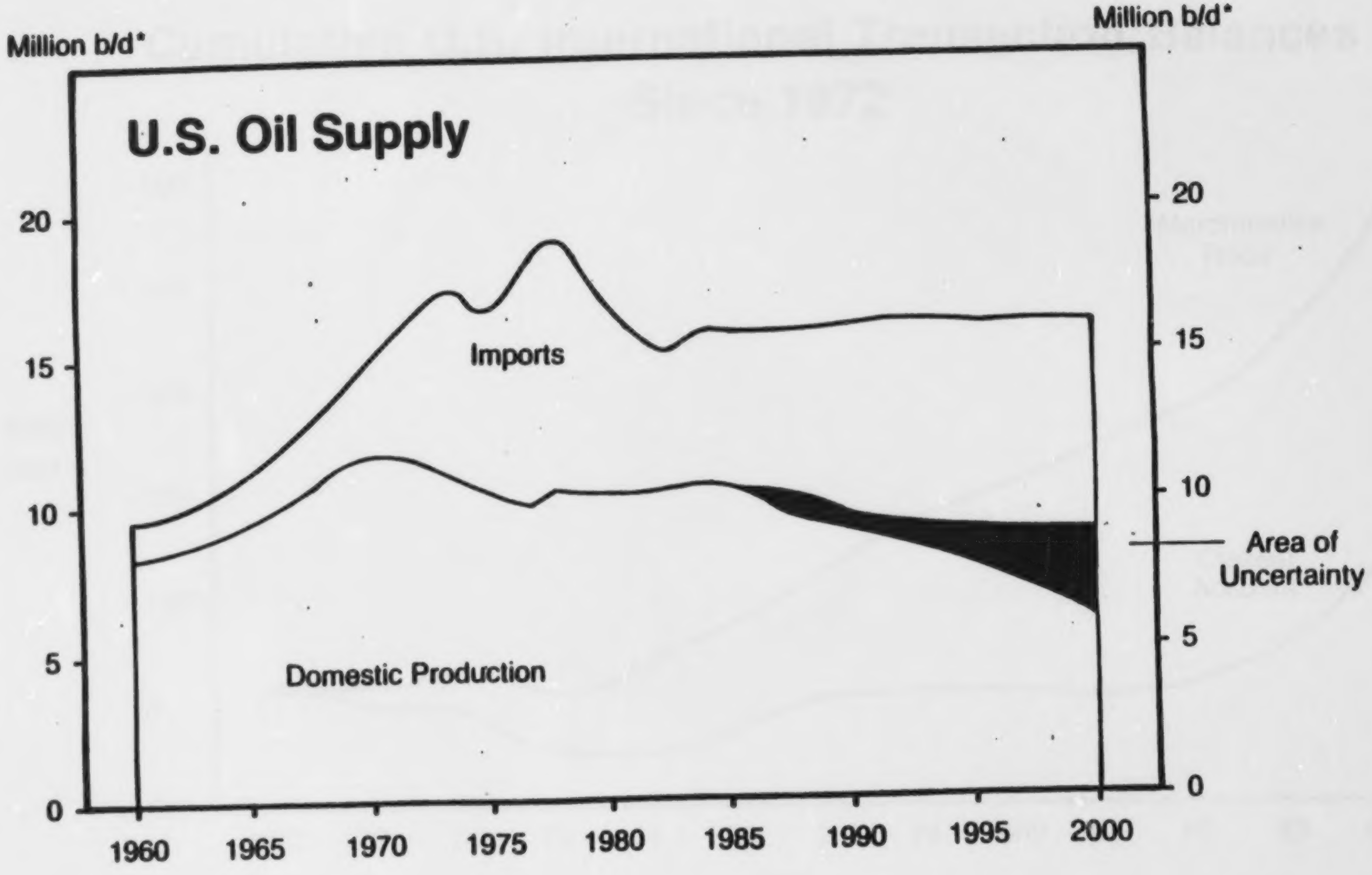
EPA has performed an analysis to determine when methanol fuel might become competitive with diesel fuel for use in transit buses. Our analysis utilized the following assumptions: 1) Methanol buses will need only the addition of a catalytic converter to meet the 1991 emission standards, 2) The addition of a converter and a larger fuel tank will raise the cost of a methanol bus by approximately $1000, 3) Methanol buses would achieve energy efficiencies equal to today's uncontrolled diesel buses, 4) Delivered methanol fuel cost to transit authorities in the 1990s would be $0.60 per gallon, based on the large surpluses projected to exist, and 5) Diesel buses would require particulate traps and NOx emission controls to meet the 1991 standards, which will raise the cost of diesel bus engines by $1000 to $3000 and will decrease fuel economy by from 3 to 9 percent.

Based on these assumptions, the "break-even" diesel fuel price would be in the range of $1.23 to $1.33 per gallon. In other words, if diesel fuel cost more than $1.33 per gallon, then methanol fueling would be cheaper. If diesel fuel cost less than $1.23 per gallon, then diesel would continue to be cheaper. Average diesel fuel prices between $1.23 and $1.33 per gallon could result in either methanol or diesel fueling being more efficient depending upon various factors. Energy experts still expect world oil prices to climb in the early 1990s, and diesel fuel prices could certainly exceed $1.33 per gallon by the mid 1990s.

Conclusion

Evidence is mounting that diesel transit bus emissions are of much greater public health concern that previously believed. In view of the relatively high public exposure of urban residents to diesel bus emissions, as well as Congressional directives to control such emissions, EPA has promulgated much more stringent emission standards to take effect in 1991. For the first time, there is a real alternative to the diesel bus which offers several environmental advantages. It appears that methanol buses would provide significant reductions of particulate, smoke, and NOx emissions, and would likely reduce the ozone-formation potential of urban atmospheres. Methanol bus engine efficiencies are expected to equal, and possibly exceed, those of diesel bus engines, and based on current energy price projections methanol buses could be cheaper to operate by the mid 1990s. EPA supports methanol bus research by the automotive industry and strongly urges that transit authorities consider methanol as one alternative for the 1990s.

FIGURE 1



*Million barrels/day

FIGURE 2

Cumulative U.S. International Transaction Balances Since 1972

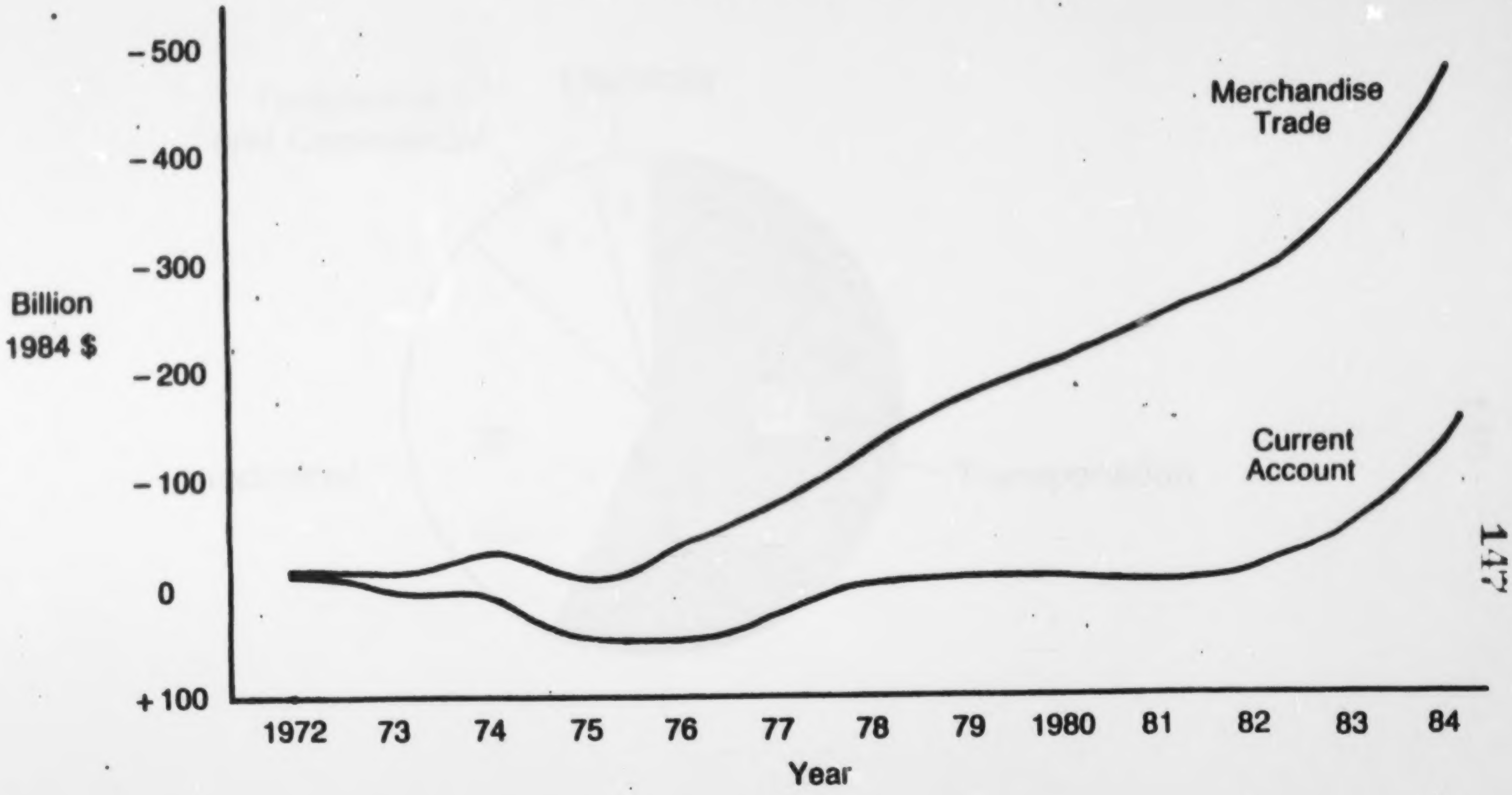


FIGURE 3

U.S. Petroleum Consumption by Sector, 2000

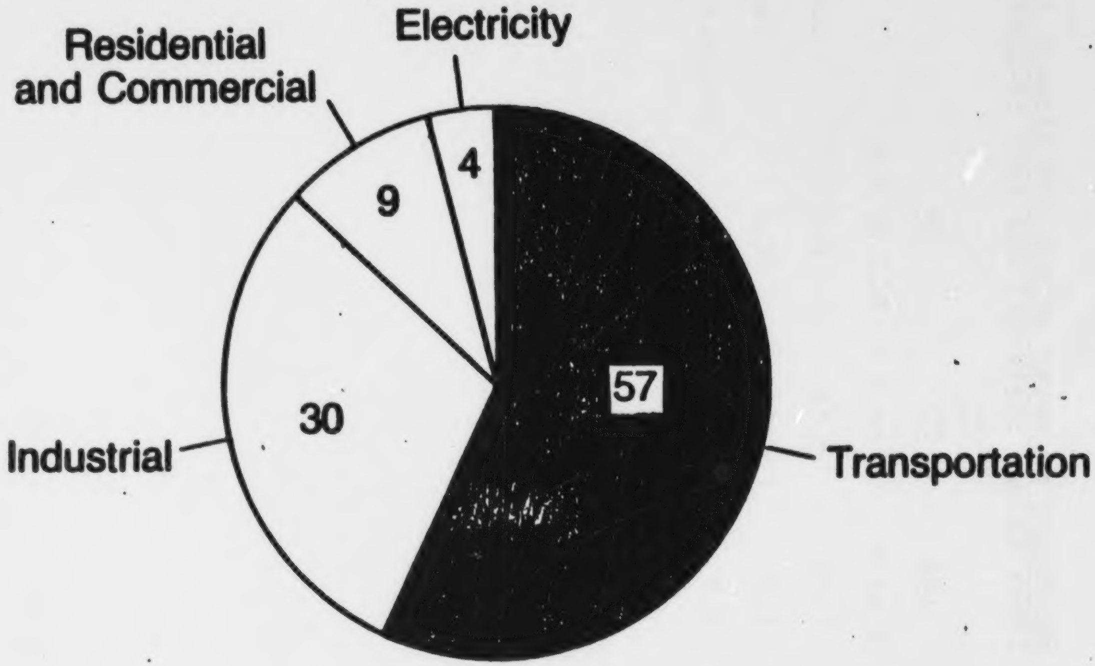


Table 1

EPA Transit Bus Engine Emission Standards
(g/bhp-hr over EPA transient engine test)

	HC	CO	NOx	PM
Current engines	0.5 to 1.0	1 to 5	5 to 9	0.4 to 0.8
1985-1987 standard	1.3	15.5	10.7	none
1988-1990 standard	1.3	15.5	6.0	0.6
1991 and later standard	1.3	15.5	5.0	0.1

Table 2

Recoverable Fossil Fuel Resource Distribution in the United States

Resource	Percentage of Total Recoverable Fossil Fuel Energy*	Percentage of Total Recoverable Fossil Fuel Energy+
Coal	91.2	81.7
Oil Shale	2.8	12.9
Crude Oil	2.2	2.0
Conventional Natural Gas	2.2	2.0
Unconventional Gas	1.6	1.4

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*Including only those oil shale resources containing over 30 gallons of oil per ton.

+Including only those oil shale resources containing over 15 gallons of oil per ton.

Table 3

Diesel Bus Engine vs. Chassis Emissions
(EPA transient test procedures)

Pollutant	New Diesel Bus Engines (g/bhp-hr)	In-Use Diesel Bus Chassis (g/mile)
HC	1.51	3.35
CO	3.22	51.9
NOx	6.25	26.1
PM	0.57	5.52

Table 4

New Diesel vs. Methanol Bus Engine Emissions
(g/bhp-hr)

Pollutant	Diesel Bus Engines	MAN Methanol Bus Engine	GM Methanol Bus Engine
PM	0.57	0.04	0.17
NOx	6.25	6.60	2.20
CO	3.22	0.31	-
Organics	1.61	0.68	1.28
HC	1.51	0.001	-
Methanol	0	0.68	1.13
Aldehydes	0.10	0.001	0.15

Table 5

In-Use Diesel vs. Methanol Bus Chassis Emissions
(g/mile)

Pollutant	Diesel Bus Chassis	MAN Methanol Bus Chassis	GM Methanol Bus Chassis
PM	5.52	0.09	1.09
NOx	26.1	13.6	7.90
CO	51.9	0.65	107
Organics	3.88	1.40	120
HC	3.35	0.09	1.15
Methanol	0	1.16	116
Aldehydes	0.53	0.15	2.33

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ABSTRACT

Emissions from the two methanol-powered buses used in the California Methanol Bus Demonstration have been characterized. The M.A.N. SU 240 bus is powered by M.A.N.'s D2566 FMUH methanol engine, and utilizes catalytic exhaust aftertreatment. The GMC RTS II 04 bus is powered by a first-generation DDAD 6V-92TA methanol engine without exhaust aftertreatment. Emissions of HC, CO, NO_x, unburned methanol, aldehydes, total particulates, and the soluble fraction of particulate were determined for both buses over steady-state and transient chassis dynamometer test cycles. Emission levels from the M.A.N. bus were considerably lower than those from the GMC bus, with the exception of NO_x. Comparison of emission levels from methanol-and diesel-powered buses indicates that substantial reductions in emissions are possible with careful implementation of methanol fueling.

DIESEL ENGINES have been used with petroleum fuels for nearly a century, yet in some applications, high levels of particulate and NO_x emissions persist along with nuisance emissions of smoke and odor. Diesel-powered buses are one of the prime examples of a diesel engine application which has come under scrutiny due to concerns about emissions. In the interest of reducing emissions and dependence on imported oil, the California Energy Commission (CEC) has undertaken demonstrations of advanced fuel technologies with particular emphasis on the use of methanol, a clean burning and efficient transportation fuel which can be produced from a variety of U.S. feedstocks.

One of these demonstrations involved two neat methanol-powered transit buses, with one bus developed by Maschinenfabrik Augsburg-Nurnberg (M.A.N.) of the Federal Republic of Germany and the other by General Motors Corporation (GMC). Both methanol buses were placed in revenue transit service by the Golden Gate Bridge Highway and Transportation District, to demonstrate the feasibility of operating methanol-fueled buses in such service. The objective of this work was to characterize the emissions behavior of these two methanol-fueled buses during chassis dynamometer operation at four steady-state conditions and on two transient test cycles on behalf of EPA.(1)*

ANALYTICAL PROCEDURES for emission measurements were based on procedures established for the 1984 transient testing of heavy-duty engines(2), and on procedures outlined in EPA's "Recommended Practice for Determining Exhaust Emissions from Heavy-Duty Vehicles Under Transient Conditions"(3) for heavy-duty chassis dynamometer testing of vehicles. A large single-dilution CVS was used to obtain mass proportional emissions samples. Extremely low particulate rates were expected, so the CVS dilution tunnel and the associated sampling systems normally used for diesel engine emissions sampling were cleaned to reduce the potential for particulate sample interference due to tunnel background particulate.

Total hydrocarbons were determined over each test cycle by integration of continuous hydrocarbon measurements of the CVS-diluted exhaust. These hydrocarbon concentrations were measured using a Beckman 402 heated flame ionization detector (HFID), calibrated on propane. Normally, the heated sample train is maintained near 375°F. However, since methanol undergoes increased dissociation into hydrogen and CO at temperatures above 250°F,(4) the continuous HC sample train was maintained near 175°F for this program. Total hydrocarbon emissions are generally assumed to be of the same general composition as the fuel used, and therefore it is assumed here that all of the gaseous "hydrocarbons" are methanol vapor. Thus, a HC density of 37.7 g/ft^3 was used in computation of HC mass from concentration (ppm C) levels obtained by HFID analysis. Results obtained using the measured concentrations were increased by a factor of 1.25 to account for the

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*Numbers in parentheses designate references at the end of the paper.

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0.80 response of the HFID to methanol (based on a 90 ppm methanol-in-air gas). The mass emission of "HC" represents the methanol molecule and includes the mass of oxygen associated with methanol. To differentiate this value from individual hydrocarbon species (discussed later), the term "FID HC" will be used for total HFID measured hydrocarbons.

Unburned methanol samples were collected by bubbling CVS-diluted exhaust gases through distilled water. Concentrations of unburned methanol were determined with a gas chromatograph using an FID specifically calibrated for quantitative purposes. In addition, proportional bag samples of dilute exhaust gases were analyzed for selected individual hydrocarbons (IHC) including methane, ethane, ethylene, acetylene, propane, propylene, benzene, and toluene.(5) The 2,4-dinitrophenylhydrazine (DNPH) method(5) was used to determine levels of formaldehyde, acetaldehyde, acrolein, acetone, propionaldehyde, isobutyraldehyde, methylethylketone, crotonaldehyde, hexanaldehyde, and benzaldehyde. The emission rates of these individual hydrocarbon and aldehyde species were then summed to yield total IHC and total aldehyde emissions, respectively.

Concentrations of CO and CO_2 in proportional dilute exhaust bag samples were determined by nondispersive infrared (NDIR) instruments. NO_x emissions were determined from integration of continuous concentration monitoring of the CVS-diluted exhaust by use of a chemiluminescence (CL) instrument. NO_x correction factors for intake humidity were applied as specified in the 1984 transient FTP.(2)

Emission levels for HC, CO, CO_2, and NO_x were processed along with CVS flow parameters and bus operating parameters to compute mass emissions on the basis of distance and fuel usage. These computations were based on the equations specified in the Federal Register for exhaust emissions from gasoline or diesel exhaust.(2) However, the equations were modified per "Calculation of Emissions and Fuel Economy when Using Alternate Fuels" (EPA Report No. 460/3-83-009)(6) in order to account for the use of an oxygenated fuel. Using these modified equations, fuel consumption was computed on the basis of carbon balance.

Particulate emissions were determined from dilute exhaust samples utilizing various collection media and apparatus. Total particulate mass samples were collected on 47 mm Pallflex T60A20 fluorocarbon-coated glass fiber filter media, by means of a single-dilution technique. A sample of total particulate matter was collected on a 47 mm Fluoropore filter for the determination of metals and other elements by x-ray fluorescence. To determine the soluble organic fraction (SOF) of the total particulate, large particulate-laden filters (20x20 inch Pallflex T60A20) were extracted with methylene chloride. The boiling point distribution of the SOF was determined using a high-temperature variation of ASTM-D2887-73 (a gas chromatograph method).

CHASSIS DYNAMOMETER TEST PROCEDURES used in this program were based on procedures outlined in EPA's "Recommended Practice for Determining Exhaust Emissions From Heavy-Duty Vehicles Under Transient Conditions."(3) The chassis dynamometer used in this program was a tandem-axle Clayton heavy-duty unit modified by the addition of eddy current power absorbers and directly coupled inertia wheels. Selective coupling of inertia wheels provided appropriate inertia simulation. Electronic programming of the system enabled application of the computed road-load speed-power curve (based on previous documentation(7)).

Both methanol buses were tested over six chassis cycles or operating conditions. Steady-state operation included cold idle, 20 kilometer per hour (kph), 40 kph, and hot idle conditions. Transient operation included the DOT central business district (CBD) cycle and the EPA bus cycle. All test work was conducted with the air conditioning and all other normally controlled accessories turned off.

The cold-idle steady-state was conducted with the transmission in neutral position. Emissions sampling commenced with engine cranking and start of the engine. The engine was allowed to idle in neutral and emission samples were taken for 15 minutes. Although it is unlikely that a 15-minute idle in neutral would occur in field operation, the prolonged idle was used to accumulate adequate samples for analysis. The term "cold," as it is used in this report, refers to the engine being allowed to stand overnight in an ambient temperature between 20 and 30°C (68 to 86°F) prior to and during engine start-up. No attempt was made to cause fast engine warm-up over the "cold-idle" period.

After completing cold-idle emissions sampling, the bus was operated in a warm-up mode, then held at 80 kph to check the dynamometer load setting. Once the load was confirmed, emissions testing proceeded with the 20 kph steady-state, then the 40 kph steady-state and finally the hot-idle steady-state. The hot-idle steady-state was conducted with the transmission in "drive" and the brakes set. Emission samples were collected over a 15-minute period at each condition to allow adequate time for sample accumulation (although a 15-minute idle may not occur in actual use, the emission rate determined from this testing should be valid for shorter idle periods).

Emission samples were also taken over the CBD and bus cycles. The CBD cycle is one of four transit coach operating profile duty cycles adopted by the Urban Mass Transportation Administration of the U.S. DOT for evaluation of bus operation and fuel economy.(8) For this work, the CBD cycle was composed of 14 repetitions of the basic cycle, which included idle, acceleration, cruise, and deceleration modes. An example of this basic cycle is given in Figure 1, and it was repeated 14 times for a chassis driving cycle time of 580 seconds and a distance of 2.0 miles (3.2 km).

Data accumulated from bus operation (CAPE-21)(9) were used by EPA to develop a "heavy-duty chassis bus driving cycle."(10) The driving schedule shown in Figure 2 was used in this program and called the "Bus Cycle." Of the 1191-second duration of the cycle, a total of 394 seconds are at idle with the transmission in "drive." The distance of the bus cycle is 2.90 miles. The maximum speed called for by the cycle is 36 mph. The bus cycle contains many sharp accelerations and decelerations requiring full accel-

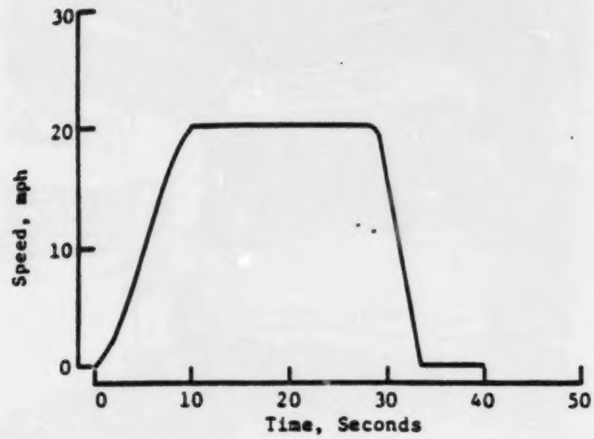

Figure 1 - One segment of the CBD test cycle

erator pedal deflection one moment and braking the next.

BOTH METHANOL POWERED BUSES were tested for emissions after approximately two years of revenue service in the San Francisco area. The methanol buses were transported to and from California by truck-trailer due to the lack of maintenance support and fuel supply enroute. Both buses were received with on-board tanks full of "fuel quality" neat methanol provided from the bulk supply fuel point at the Golden Gate Transit garage. Upon arrival, each bus was off-loaded, and a basic operational check was performed, allowing the driver to become familiar with the controls. Each bus was driven to a public scale for weight determination and returned to the laboratory for dynamometer set-up. Some of the pertinent descriptive information on both buses is given in Table 1.

Table 1 - Methanol Bus Specifications and Test Weights

Manufacturer	M.A.N.	GMC
Model	SU 240	RTS II 04
Length, m (ft)	11.6(38)	12.2 (40)
Passenger Cap. (seated)	49	43
Transmission Model	Voith D 854	Allison V730D
Axle Ratio	5.936	4.556
Tire Size	11R 22.6 x 2A	12.5 x 22.5
Engine Model	M.A.N. D2566 FMUH	DDAD 6V-92TA Methanol
Displacement, liter	11.6	9.05
Rated Power, kW @ rpm	147 @ 2200	207 @ 2100
Engine Cycle	4-Stroke	2-Stroke
Compression Ratio	18:1	19:1
Ignition System	Spark	Compression[b]
Intake Air	Naturally Aspirated	Turbo & Blower
Service Accum., km (miles)	45,500 (28,300)	30,500 (18,900)
Curb Weight[a], kg (lb)	11,100 (24,500)	13,000 (28,700)
Test Inertia, kg (lb)	12,800 (28,300)	14,800 (32,600)

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[a] Weight as received with fuel tanks filled, bus empty

[b] With glow plug assist at light loads plus scavenging air management

THE M.A.N. METHANOL BUS, shown in Figure 3, is a model SU 240 powered by a M.A.N. D2566 FMUH engine developed for consuming a variety of low-cetane fuels. The methanol engine is based on a M.A.N. diesel engine design and has an 18:1 compression ratio. Ignition of the methanol is accomplished by a timed spark ignition system.(11) This naturally aspirated, four-stroke, in-line 6-cylinder engine is essentially the same as that tested on an engine dynamometer in an earlier EPA program.(12) Figure 4 shows the engine compartment of the M.A.N. SU 240 methanol bus with the horizontal configuration of the engine. Power for air conditioning on the bus is supplied by a small auxiliary diesel engine.

The M.A.N. bus uses a catalyst for exhaust aftertreatment to reduce emission of unburned methanol and aldehydes. The catalyst formulation was provided by Engelhard, and was designated as a "diesel oxidation catalyst containing 1770 g/m^3 of platinum." The catalyst assembly utilized Corning M 20/400 ceramic monolith substrate, and has a volume of 5.7 liters. Prior to transport, a new catalyst assembly was installed to replace one which had failed due to loss of spark ignition. After routine maintenance, operation and driveability of the bus were deemed typical and acceptable before shipment for testing.

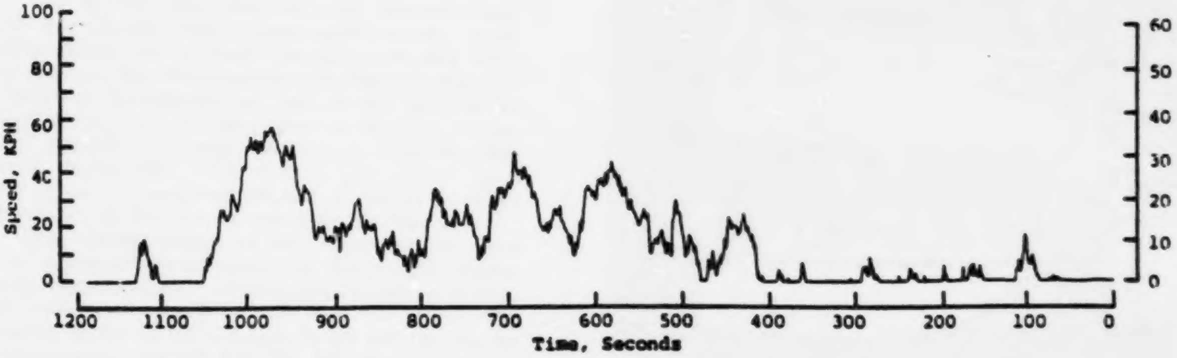

Figure 2 - Heavy-duty chassis bus driving cycle

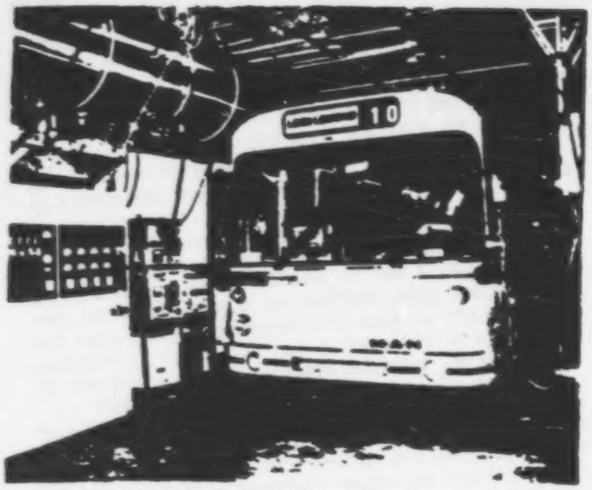

Figure 3 - M.A.N. SU 240 methanol bus positioned for emissions testing

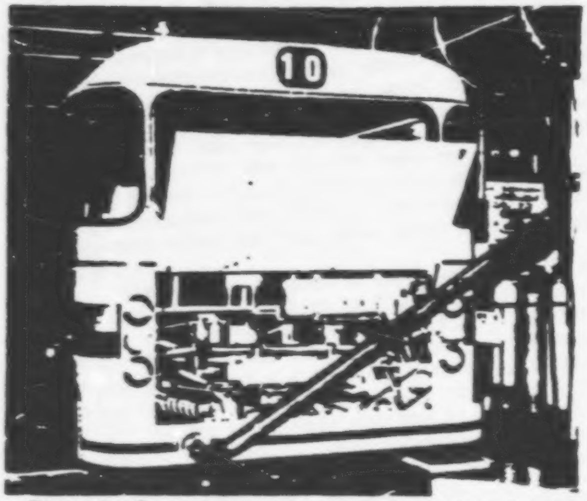

Figure 4 - Engine compartment of the M.A.N. SU 240 methanol bus with exhaust routed to CVS

The M.A.N. was received with approximately 45,500 km (28,300 miles) accumulated usage. After familiarization and a check that all spark plug wires were in place, the driver started the bus according to the start-up procedures outlined in the instructions (essentially to turn on the power to the fuel pumps, wait 5 seconds, and start the engine with the foot throttle depressed). The M.A.N. was driven to a public scale and weighed (24,470 lb total). Overall performance of the M.A.N. methanol bus was good.

The inertia wheels of the dynamometer were set for a simulation of 12,834 kg (28,300 lb), representing approximately 25 passengers and a driver. Total road load power at 80 kph (50 mph) was computed to be 58 kW (78 hp); 31 kW (42 hp) due to air resistance, and 27 kW (36 hp) due to rolling resistance. The dynamometer controls were adjusted to approximate the computed road load curve of the bus.

Cold-start of the M.A.N. methanol engine went well, and "good" engine idle quality was observed. Engine operation was "good" over all operating test conditions. The driver was able to follow both the CBD and bus cycle transient driving schedules in a satisfactory manner.

THE GMC METHANOL BUS, shown in Figure 5, is a model RTS II 04, which is typical of the majority of city transit buses used in the United States. The methanol engine was developed from the GMC Detroit Diesel Allison Division (DDAD) 6V-92TA diesel engine. The DDAD 6V-92TA (turbocharged, aftercooled) methanol engine shown in Figure 6 is of two-stroke design and depends on compression ignition of methanol. Compression ignition of methanol occurs unassisted during high load conditions. The

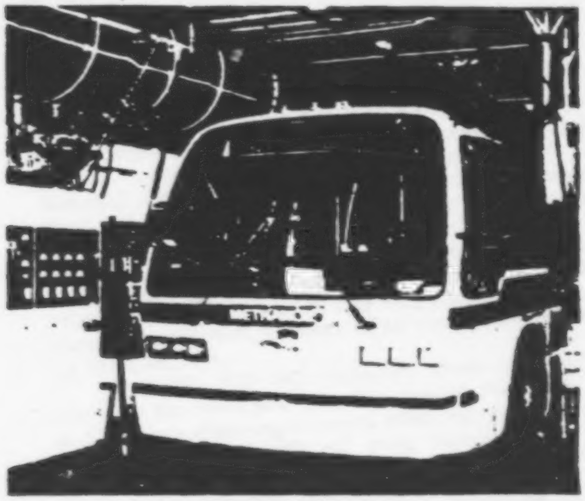

Figure 5 - GMC RTS II 04 methanol bus positioned for emissions testing

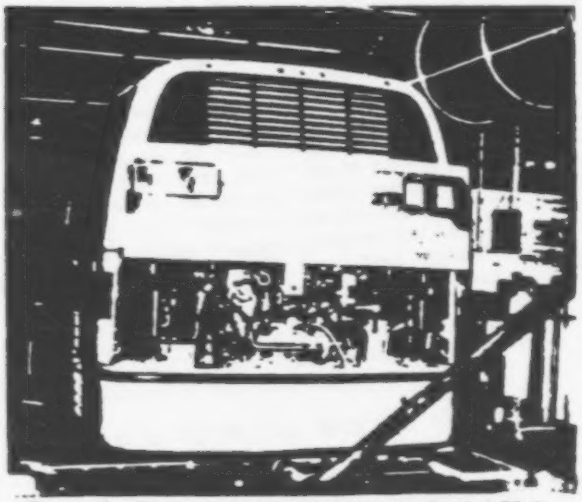

Figure 6 - Engine compartment of the GMC RTS II 04 methanol bus with exhaust routed to CVS

design relies on control of scavenging air to maintain ignition during moderate and light loads. In addition, glow plugs are used to assist light load, idle and start-up operation of the GMC methanol engine. The methanol engine utilizes electronically controlled injectors. The GMC methanol bus uses an on-board computer to vary scavenging air, glow plug operation, fuel delivery, and injection timing relative to throttle demand and engine parameters.(13,14)

No catalyst aftertreatment was used on the GMC methanol bus. Prior to shipment, preventive maintenance was conducted on the GMC methanol bus, including checks of the glow plug voltages and the parameters monitored and used by the on-board computer. Operation and driveability were deemed typical and acceptable before shipment for testing.

The GMC bus was received with approximately 30,400 km (18,900 miles) accumulated usage. After familiarization, the GMC methanol bus engine was started according to the instructions provided. The starting procedure basically called for turning on the glow plugs for approximately 1-2 minutes, then engaging the starter. If a false start was encountered, the sequence was repeated. Once the bus was started, the engine was under the control of the on-board computer and would not respond to accelerator pedal movement until after about 2 to 5 minutes. Idle quality was very rough until the engine oil warmed up. After about 15 minutes of low speed idle, engine idle quality improved. Initially the improvement in idle quality was not as good as expected, and it was determined that one of the glow plug connections was faulty. The warm idle quality improved when all the glow plugs were working properly.

The bus was weighed at the public scale (28,650 lb total), then driven back to the laboratory. Inertia wheels of the dynamometer were set for a simulation of 14,784 kg (32,600 lb), representing approximately 25 passengers with a driver. Total road load power at 80 kph (50 mph) was computed to be 60 kW (80 hp); 29 kW (39 hp) due to air resistance and 31 kW (41 hp) due to rolling resistance. The dynamometer controls were adjusted to approximate the road load curve computed for the GMC methanol bus.

The GMC bus was equipped with a diagnostic data link (DDL). Some of the outputs from the DDL reader were recorded during steady-state operation and are summarized in Table 2. "Pulse width" information (the number of crank angle degrees that the injectors are supplying fuel) indicated more fuel was injected during the cold-start idle in neutral than was injected during the hot idle in drive. From "beginning of injection" (injection timing in degrees BTDC) information, it appears that the methanol bus engine timing was substantially retarded from that reported by Toepel, et al, during development work on the GMC methanol engine.(13) Exhaust temperature data indicated cylinder-to-cylinder combustion imbalance on this prototype engine.

The GMC bus performed reasonably well with the exception of cold idle in neutral. Cold start-up was accomplished with no problem, and the engine did not stall. Aside from the rough idle during warm-up, the general performance was regarded as "acceptable" by the driver. The driver was able to follow both the CBD and bus cycle transient driving schedules in a satisfactory manner.

Table 2 - GMC Methanol Bus Diagnostic Data Link (DDL) Reader Output[a]

Parameters	Cold Idle	[illegible]	[illegible]	Hot Idle
Engine Speed, rpm	710-820	914-973	1262-1271	601-632
Compressor Pressure, kPa	47	30	70	47
Oil Temperature, °C	61-80	88	80-83	89
Air Temperature, °C	25-33	30-40	30-40	30-40
Throttle Position, [illegible]	30	36	70	30
Pulse Width, °crank	6.5-6.6	6.8-7.2	8.8-8.9	3.9-4.6
Beginning of Injection, °crank	8.8-8.3	6.5-6.6	3.5-7.5	6.8-7.8
Cyl. Exhaust Temp., °C				
1	175	206	196	103
2	196	250	206	101
3	180	218	278	130
4	170	262	318	132
5	200	263	402	184
6	187	242	230	130

[a] Observed over 3 separate runs

EMISSION RESULTS from the M.A.N. and the GMC methanol buses are summarized in Tables 3 and 4, respectively. Cold idle emissions included engine start-up and low-speed idle operation with the transmission in neutral for a total of 15 minutes. FID hydrocarbon levels during cold idle operation of the M.A.N. were relatively high for a short time (1-3 minutes) after start-up, then tapered off and stabilized. Based on very low FID HC levels observed during the warm engine/warm catalyst operation that followed, it appears that the M.A.N. catalyst was not functioning during the cold idle conditions. Even so, cold-idle emission levels of FID HC, CO, and particulate from the M.A.N. were significantly lower than for the GMC bus.

Cold-idle FID HC emissions from the GMC methanol bus were also very high during the initial 2 to 5 minutes after engine start, when the engine idled very roughly. The FID HC level tapered down to about half the initial peak level and remained stable for 13 to 15 minutes, coinciding with improved but still somewhat erratic idle quality. After 13 to 15 minutes the idle quality smoothed and the FID HC level dropped again. These changes in FID HC levels and idle quality corresponded with changes in engine operation controlled by the on-board computer.

The high levels of FID HC emitted by the GMC (6 times those from the M.A.N.) during the cold idle represent a significant portion (about 20 percent) of the fuel consumed. In addition, the extremely low emissions of NO_x from the GMC during cold idle operation were likely due in part to poor combustion. Cold-idle particulate emissions for the M.A.N. were very low. Cold-idle particulate levels for the GMC were higher than expected on the basis of consuming neat methanol. It is likely that engine lubricating oil was scavenged out into the exhaust and caused the higher-than-anticipated particulate emissions. Emission results from warm engine testing of the M.A.N. and GMC were significantly different from those achieved in cold idle testing.

M.A.N. METHANOL BUS FID HC emission levels during warm engine testing were very low at about 1 g/kg fuel, or less than 1 g/km. Carbon monoxide emissions were essentially negligible. Low levels of

Table 3 - Summary of Emissions from the M.A.N. SU 240 Methanol Bus

Chassis Test Procedure	Steady-State Operation				Transient Cycles	
	Cold Idle	Hot Idle	20 kph	40 kph	CBD	Bus
Hydrocarbons,[a] FID HC[d] g/km, (g/hr), [g/kg fuel]	(225) [32]	(4.6) [0.65]	0.63 [0.93]	0.45 [1.1]	0.53 [0.54]	0.85 [1.00]
Carbon Monoxide, CO g/km, (g/hr), [g/kg fuel]	(56) [8.0]	(2.3) [0.3]	0.31 [0.4]	0.21 [0.5]	0.48 [0.5]	0.33 [0.4]
Oxides of Nitrogen, NO_x[d] g/km, (g/hr), [g/kg fuel]	(47) [6.6]	(67) [9.4]	3.3 [4.8]	2.4 [5.5]	8.8 [8.9]	8.1 [9.5]
Fuel Economy[b] km/kg, (kg/hr)	(7.0)	(7.2)	1.5	2.3	1.0	1.2
Diesel Fuel Equivalent[c] km/kg, (kg/hr)	(3.2)	(3.3)	3.2	5.1	2.2	2.6
Total Individual HC mg/km, (mg/hr), [mg/kg fuel]	(840) [120]	(41) [5.7]	43 [65]	4.0 [9.3]	79 [80]	28 [32]
Total Aldehydes g/km, (g/hr), [g/kg fuel]	(14) [2.0]	(2.1) [0.30]	0.18 [0.28]	0.039 [0.092]	0.10 [0.10]	0.084 [0.098]
Unburned Methanol g/km, (g/hr), [g/kg fuel]	(230) [33]	(8.5) [1.2]	1.6 [2.4]	0.49 [1.1]	0.35 [0.36]	1.1 [1.5]
Total Particulate g/km, (g/hr), [g/kg fuel]	(0.58) [0.08]	(0.81) [0.11]	0.04 [0.05]	0.02 [0.06]	0.06 [0.06]	0.04 [0.05]
Soluble Organic Fraction g/km, (g/hr), [g/kg fuel]	(0.58) [0.08]	(0.09) [0.01]	0.01 [0.01]	0.01 [0.02]	0.02 [0.02]	0.02 [0.02]

[a] HC emissions have been increased to account for the 0.8 response factor of the FID to methanol, and are based on a molecular weight of 32

[b] Fuel consumption figures were computed by carbon balance, km/kg methanol may be converted to mi/gal methanol by multiplying by 1.86

[c] Diesel fuel equivalent was computed using a heating value ratio of 2.17

[d] Based on continuous measurement

both FID HC and CO indicate that the engine/catalyst package was working well. It should be noted that emissions during the hot idle in "drive" were stable, and indicated that the catalyst continued to function steadily for a relatively long idle period. Emissions of NO_x from the M.A.N. over all test operation ranged from 4.8 to 9.5 g/kg fuel, or 3.3 to 8.8 g/km. Particulate emissions from the M.A.N. for all tests were very low, ranging from 0.05 to 0.11 g/kg fuel, or 0.02 to 0.06 g/km. These levels were in the same range as noted for the M.A.N. D2566 FMUH methanol engine tested on behalf of EPA by SwRI in 1982.(12)

The highest average level of unburned methanol emitted for the M.A.N. was 33 g/kg of methanol during the cold-idle, representing 3.3 percent of the fuel consumed. During the warm engine operating conditions with the M.A.N., where the catalyst was known to be working, the unburned methanol levels were substantially lower and represented less than 0.2 percent of the fuel consumed.

For the M.A.N., methane was the predominant individual hydrocarbon emitted; and it was greatest during the cold idle. Methane was also noted to a lesser extent over the CBD, 20 kph, and bus cycle operations. Small concentrations of ethane were noted along with an indication that ethylene and propane may be present over some conditions. Formaldehyde was the predominant individual aldehyde emission for the M.A.N. bus, essentially representing the "total aldehydes."

For the M.A.N, the SOF portion of the total particulate accounted for essentially all of the particulate emissions during the cold idle condition. For warm engine/catalyst operation of the M.A.N., the SOF ranged from about 10 to 50 percent of the total particulate.

Table 4 - Summary of Emissions from the GMC RTS II 04 Methanol Bus

Chassis Test Procedure	Steady-State Operation				Transient Cycles	
	Cold-Idle	Hot-Idle	20 kph	40 kph	CBD	Bus
Hydrocarbons,[a] FID HC[d] g/km, (g/hr), [g/kg fuel]	(2,900) [230]	(660) [100]	150 [180]	140 [190]	75 [53]	92 [61]
Carbon Monoxide, CO g/km, (g/hr), [g/kg fuel]	(440) [35]	(290) [46]	32 [38]	27 [38]	55 [39]	78 [51]
Oxides of Nitrogen, NO_x[d] g/km, (g/hr), [g/kg fuel]	(19) [1.5]	(3.6) [0.6]	1.3 [1.6]	1.6 [2.3]	4.9 [3.5]	4.9 [3.2]
Fuel Economy[b] km/kg, (kg/hr)	(13)	(6.5)	1.2	1.4	0.71	0.65
Diesel Fuel Equivalent[c] km/kg, (kg/hr)	(6.0)	(3.0)	2.6	3.1	1.5	1.4
Total Individual HC mg/km, (mg/hr), [mg/kg fuel]	(3,000) [230]	(1,600) [250]	170 [200]	110 [160]	600 [450]	820 [540]
Total Aldehydes g/km, (g/hr), [g/kg fuel]	(35) [2.7]	(23) [3.5]	2.4 [2.9]	1.2 [1.8]	1.2 [0.89]	1.7 [1.1]
Unburned Methanol g/km, (g/hr), [g/kg fuel]	(2,700) [210]	(380) [58]	110 [170]	120 [170]	62 [44]	82 [54]
Total Particulate g/km, (g/hr), [g/kg fuel]	(6.8) [0.52]	(3.8) [0.58]	0.33 [0.39]	0.19 [0.27]	0.96 [0.69]	0.39 [0.25]
Soluble Organic Fraction g/km, (g/hr), [g/kg fuel]	(5.7) [0.44]	(3.0) [0.47]	0.28 [0.33]	0.16 [0.22]	0.84 [0.60]	0.33 [0.21]

[a] HC emissions have been increased to account for the 0.8 response factor of the FID to methanol, and are based on a molecular weight of 32

[b] Fuel consumption figures were computed by carbon balance, km/kg methanol may be converted to mi/gal methanol by multiplying by 1.86

[c] Diesel fuel equivalent was computed using a heating value ratio of 2.17

[d] Based on continuous measurement

THE GMC METHANOL BUS did not utilize a catalyst for exhaust aftertreatment. FID hydrocarbon emission levels from warm engine testing of the GMC methanol bus were very high compared to the M.A.N.. The conditions of cold idle, 20 kph, and 40 kph all had notably higher levels of FID HC than the hot idle in "drive," bus cycle, or CBD cycle. Carbon monoxide from warm engine operation of the GMC methanol bus ranged from 38 to 51 g/kg fuel. Warm engine emissions of NO_x were extremely low for the GMC bus, ranging from 0.6 to 3.5 g/kg fuel. Lower NO_x emissions is one of the potential emission benefits when using methanol as an engine fuel. However, low NO_x emissions can also be indicative of poor combustion quality. Particulate emission levels for the cold idle, hot idle, and CBD cycle were higher than for the 20 kph, 40 kph, and bus cycle operations. The soluble portion of the total particulate from the GMC methanol bus ranged from 80 to 90 percent over all test conditions.

Characteristics of this two-stroke cycle engine allow a certain amount of engine oil to be scavenged out into the exhaust. During prolonged idle, oil can accumulate in the air box. Much of this oil accumulation can be emitted during moderate to hard accelerations as condensible hydrocarbons, which can be collected as total particulate (SOF) and are often noted as smoke. Visible smoke was not measured during this program, mainly because no smoke emissions were expected. However, in observing the GMC methanol bus enroute to the loading point, low levels of visible smoke were noticed. The smoke levels were judged to be near 5 percent opacity, and were noted for a brief time (1 to 2 seconds) whenever the bus accelerated from a stop. (No other visible smoke was noted from either methanol bus.)

Similarities in the boiling point distributions of the SOF and engine oil, along with similarities in the metals content of total particulate samples and engine oil, indicate that a major portion of the total particulate emissions from the GMC methanol bus was engine oil.

For the GMC, the highest level of unburned methanol (0.21 kg/kg of fuel) was found at the cold idle condition, representing 21 percent of the fuel consumed. Levels of 4.4 to 5.8 percent of the fuel supplied were emitted by the GMC over the hot idle, CBD, and bus cycle operations. About 17 percent of the fuel supplied was emitted during the 20 and 40 kph cruise conditions. Methane was the predominant individual hydrocarbon found for the GMC, and was greatest during the bus and CBD cycles. Ethylene emissions were also noted over the six test conditions, averaging about 46 mg/kg fuel, with the highest levels noted for hot idle and CBD operation. Lesser levels of ethane, propane, propylene, benzene, and toluene were found, but the variabilities for these determinations were relatively high, indicating only that these species may be present under some conditions.

Formaldehyde accounted for 90 to 97 percent of the total aldehyde emissions from the GMC methanol bus. Levels were greatest for the GMC at hot idle, followed by lesser amounts for 20 kph, cold idle, 40 kph, and finally transient operation. Acetaldehyde was noted along with lesser levels of acetone, benzaldehyde, and isobutyraldehyde and methylethylketone as a group. The greater numbers of hydrocarbon and aldehyde species noted for the GMC methanol bus are likely attributable to engine crankcase oil entering into the combustion process. High unburned methanol emissions may make it difficult to apply a catalyst for exhaust aftertreatment on this engine.

FUEL ECONOMY values for both methanol buses operated at 40 kph and over the CBD cycle were computed on the basis of carbon balance, and agreed well with data obtained from road operation reported by Jackson, et al.(14) For the M.A.N., carbon balance versus road-measured fuel economy was 2.33 vs. 2.36 km/kg of methanol for the 40 kph condition, and 1.01 vs. 1.06 km/kg of methanol for the CBD cycle. For the GMC, carbon balance versus road-measured fuel economy was 1.48 vs. 1.90 km/kg of methanol for the 40 kph condition, and 0.71 vs. 0.75 km/kg of methanol for the CBD cycle. Road measurements were generated in December of 1983. The GMC methanol bus has undergone several engine/control modifications, along with mileage accumulation, since that time.

COMPARISONS OF EMISSION RESULTS obtained from the two methanol buses indicate that the M.A.N. methanol bus had significantly lower emission levels than the prototype of the first generation GMC methanol bus as already noted. A major question is, "how do the widely different emission levels from these two methanol-powered buses compare to emission levels from diesel-powered buses?" For comparison, emissions from three randomly-selected, in-service, GMC RTS II 04 buses, powered by DDAD 6V-92TA diesel engines, were determined over various chassis dynamometer conditions on behalf of EPA.(15)

The ranges of various emissions observed in testing the three diesel buses over chassis test conditions similar to those used for the methanol buses are summarized in Table 5. Emission levels of particulate, NO_x (the two pollutants of most concern from diesel engines), CO, and FID HC from the well-

Table 5 - Range of Emissions Noted from Chassis Testing of Three GMC RTS II 04 Buses Powered by DDAD 6V-92TA Engines Operated on No. 1 and No. 2 Diesel Fuel

Service, km (Oil Use, km/ℓ)	90,000 - 230,000 (700 - 1,100)				
Chassis Test Procedure	Steady-State Operation			Transient Cycles	
	Hot-Idle	20 kph	40 kph	CBD	Bus
Hydrocarbons,[a] FID HC g/km, (g/hr)	(18-40)	1.6-2.6	1.0-1.2	1.7-2.5	1.3-2.9
Carbon Monoxide, CO g/km, (g/hr)	(20-30)	1.5-3.3	1.0-1.2	10-18	6-25
Oxides of Nitrogen, NO_x[a] g/km, (g/hr)	(150-200)	10-14	7.3-9.3	14-19	13-20
Diesel Fuel Economy[b] km/kg, (kg/hr)	(3.0-3.6)	3.2-3.6	4.1-4.6	1.8-1.9	1.9-2.2
Total Aldehydes g/km, (g/hr)	(1.5-2.6)	0.10-0.20	0.05-0.10	ND	ND
Total Particulate g/km, (g/hr)	(4.0-8.0)	0.50-1.1	0.40-0.50	1.7-3.9	1.3-3.9

ND = No Data

[a] Based on continuous measurement

[b] Fuel consumption figures were computed by carbon balance

developed M.A.N. methanol bus were significantly lower than those obtained from the three diesel powered buses. Aldehyde emission levels from the M.A.N. methanol bus were generally in the range or slightly lower than noted from the diesel buses. In addition, fuel economy (on a diesel equivalent basis) also was slightly better, and no visible smoke was observed. It should be considered that the M.A.N. bus design may not compare directly to the diesel bus data given in Table 5 since there are differences in engine, chassis, and accessory design which may affect emissions.

Levels of FID HC, CO, and aldehydes from the prototype GMC bus were significantly higher than obtained from the diesel buses. However, the GMC methanol bus particulate emissions were lower than those from the diesel buses. The GMC methanol bus NO_x emissions were extremely low, but these low levels, as well as the high levels of unburned methanol and CO are thought to be in part the result of poor combustion. Fuel economy of the methanol bus (on a diesel equivalent basis) was worse than for the diesel buses. These comparisons indicate that significant development work on the first-generation 2-stroke methanol engine is necessary before the benefits of switching this engine to methanol fuel for lower emissions can be realized.

ACKNOWLEDGEMENT

We would like to express our appreciation to the California Energy Commission, Acurex, and the Golden Gate Transit Authority for their cooperation in providing the methanol buses. We also wish to thank VIA Metropolitan Transit of San Antonio and Houston Metropolitan Transit Authority for their assistance and cooperation in the testing of the methanol and diesel buses, respectively.

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OPERATIONAL ASPECTS
OF THE CANADIAN
METHANOL IN LARGE ENGINES PROGRAM

JANUARY 27-28, 1987

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LARGE ENGINE DEMONSTRATION

- A LARGE SCALE NATIONAL FIELD TRIAL COVERING ENTIRE RANGE OF HEAVY ENGINE APPLICATIONS IN THE CANADIAN OPERATING AND ECONOMIC ENVIRONMENT
- TO DETERMINE AND DEMONSTRATE THE VIABILITY OF METHANOL FUEL IN URBAN BUSES, INTERCITY BUSES, INTERCITY TRUCKS AND LARGE URBAN TRUCKS
- TO DOCUMENT THE TECHNICAL, ECONOMIC AND SOCIAL FEASIBILITY OF METHANOL
- TO PROVIDE A CLEAR UNDERSTANDING OF HOW, WHERE, WHEN AND AT WHAT COST OR BENEFIT METHANOL WILL SERVE AS AN ALTERNATIVE FUEL IN THESE MARKETS

DEMONSTRATION OBJECTIVE

TO ASSESS THE TECHNICAL, ECONOMIC AND SOCIAL FEASIBILITY OF USING METHANOL IN LARGE POWER OUTPUT ENGINES.

CONCERNS RE METHANOL:

- SAFETY, HEALTH AND ENVIRONMENT
- LIFE CYCLE COSTS
- INSTITUTIONAL AND REGULATORY CONSTRAINTS
- LACK OF INFRASTRUCTURE
- FUEL SUPPLY LOGISTICS
- COLD START AND ENGINE WEAR
- VEHICLE SYSTEMS AND OPERATIONAL REQUIREMENTS.

OPERATIONS PLAN

- Development of training and standard procedures
  - VEHICLE OPERATIONS
  - REPAIR AND MAINTENANCE
  - DATA COLLECTION
  - OIL SAMPLING
  - SAFETY
  - REFUELLING
  - DRIVEABILITY OBSERVATION
- Logistics
- Refuelling stations
- Coordination/liaison with engine, lube and fuel supplies

DATA REQUIREMENTS

- INITIAL CONFIGURATION OF VEHICLES AND SERVICES
- DAILY DATA
  - FUEL CONSUMPTION
  - DISTANCE TRAVELLED
  - DRIVING CYCLE
  - DRIVEABILITY
  - ROAD CONDITIONS AND WEATHER
- OTHER DATA
  - VEHICLE MAINTENANCE RECORDS
  - LUBE OIL ANALYSIS (WEAR METALS, CONTAMINANTS)
  - EMISSIONS
  - FUEL QUALITY

COST DATA

FUEL

LUBRICANTS

ADDITIVES

DISTRIBUTION

INFRASTRUCTURE

SPARES

TRAINING

MAINTENANCE

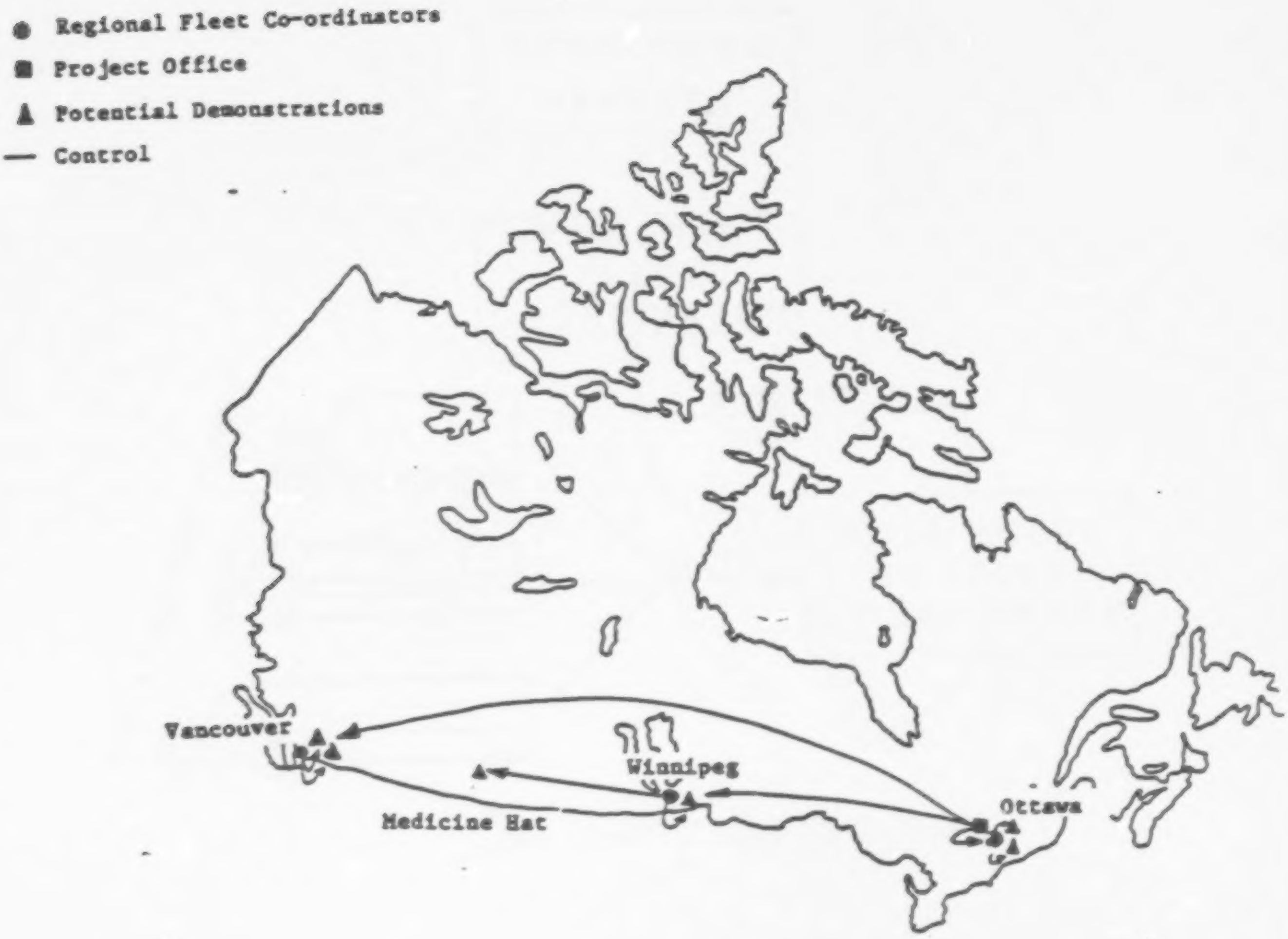
ADMINISTRATION

PERFORMANCE DATA

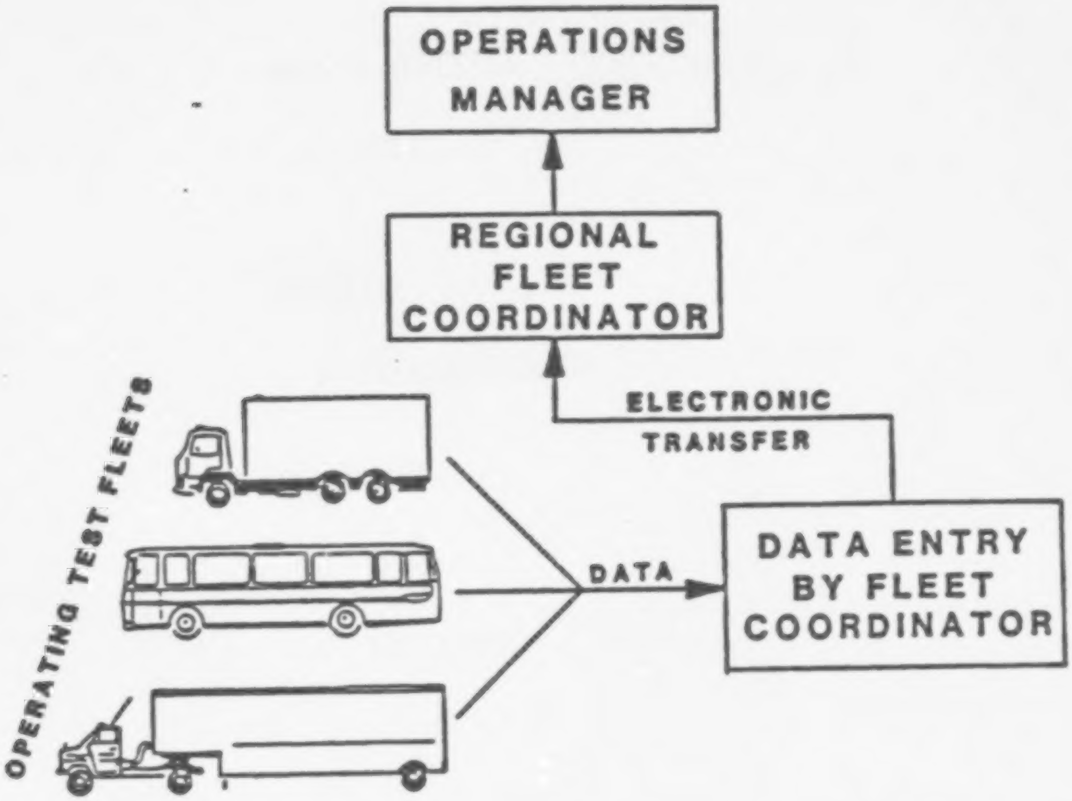
FUEL CONSUMPTION
MILES TRAVELLED
LIFE CYCLE COSTS
DRIVEABILITY
DOWNTIME

COMMUNICATIONS AND MARKETING

- LOCAL PUBLIC AWARENESS
- TECHNOLOGY DATA BASE
- TECHNOLOGY TRANSFER
- INFORMATION DISSEMINATION


● Regional Fleet Co-ordinators
■ Project Office
▲ Potential Demonstrations
— Control
Vancouver
Winnipeg
Medicine Hat
Ottawa

LOCATION OF PROJECT OFFICE, REGIONAL OFFICES, AND DEMONSTRATION FLEETS


OPERATIONS MANAGER
REGIONAL FLEET COORDINATOR
ELECTRONIC TRANSFER
OPERATING TEST FLEETS
DATA
DATA ENTRY BY FLEET COORDINATOR

DATA COLLECTION AND TRANSFER PROCESS

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MAJOR FACTORS TO CONSIDER

HEALTH EFFECTS:

- TOXICITY

SAFETY:

- FIRE/EXPLOSION

ENVIRONMENTAL:

- SPILLS
- EMISSIONS

HEALTH EFFECTS

METHANOL CHARACTERISTICS:

- TOXICITY IS GENERALLY COMPARABLE TO OR LESS SEVERE THAN THAT OF GASOLINE.

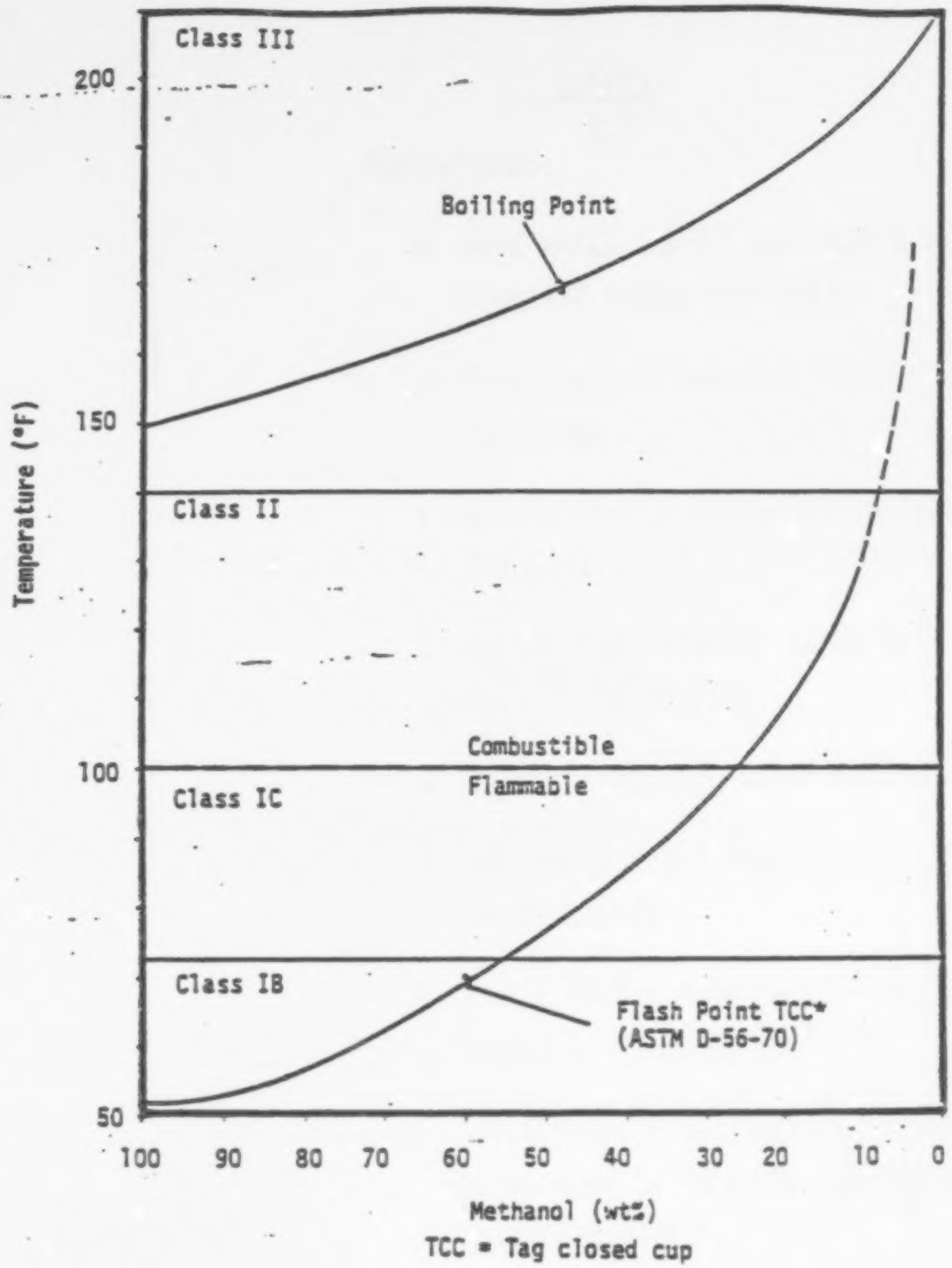
PRECAUTIONS:

- SIMILAR TO THOSE FOR GASOLINE
- ADDITIONAL PRECAUTIONS FOR MILE PROJECT
  - AVOID SPILLS ON CLOTHING AND SKIN; USE OF PROTECTIVE CLOTHING
  - USE IN WELL VENTALATED AREAS
  - HAVE WATER SUPPLY, SAFETY SHOWER AND EYE WASH FACILITIES NEAR BY
  - PROPER/DISTINCT LABELLING
  - SAFETY TRAINING FOR ALL OPERATING PERSONNEL

SAFETY

METHANOL CHARACTERISTICS:

- TOTALLY MISCIBLE IN WATER
- NO ODOUR OR TASTE
- BURNS WITH CLEAR FLAME
- WIDER FLAMMABILITY/EXPLOSIVE LIMITS THAN THOSE OF GASOLINE
- HIGHER AUTOIGNITION TEMPERATURE THAN THAT OF GASOLINE



TCC = Tag closed cup

BOILING AND FLASH POINTS OF METHANOL-WATER SYSTEMS

SAFETY

PRECAUTIONS:

- HAVE WATER SUPPLY AND PROPER FIRE-FIGHTING FOAMS AVAILABLE
- FIREFIGHTING TRAINING FOR ALL OPERATING PERSONNEL
- ENSURE PROPER GROUNDING DURING VEHICLE FUELLING
- DESIGN FUEL STORAGE TANKS WITH PROPER VENTING AND FENCING PROTECTION
- OUTDOOR FUELLING WHERE EVER POSSIBLE
- USE PRESSURIZED VEHICLE FUEL TANK CAPS IF NECESSARY
- PLACE PROPER WARNING/INSTRUCTIONAL SIGNS IN CONSPICUOUS AREAS
- INVESTIGATE FUEL FORMULATION/ADDITIVE TECHNIQUES TO ENHANCE FUEL SAFETY CHARACTERISITICS.

ENVIRONMENTAL

METHANOL CHARACTERISITICS (SPILLS):

- TOTALLY MISCIBLE IN WATER
- SPILLS ARE GENERALLY LESS DAMAGING THAN GASOLINE
- SPILLED METHANOL/WATER MIXTURES ARE FLAMMABLE WASTES AND MUST BE HANDLED ACCORDINGLY

METHANOL CHARACTERISTICS (EMISSIONS):

- CO, HC AND NO_x LEVELS ARE GENERALLY EQUAL TO OR LESS THAN THOSE FROM GASOLINE OR DIESEL FUELLED ENGINES
- SIGNIFICANTLY LOWER PARTICULATES THAN FOR DIESEL FUELLED ENGINES
- SIGNIFICANTLY GREATER ALDEHYDE EMISSIONS THAN FOR DIESEL OR GASOLINE ENGINES.

ENVIRONMENTAL

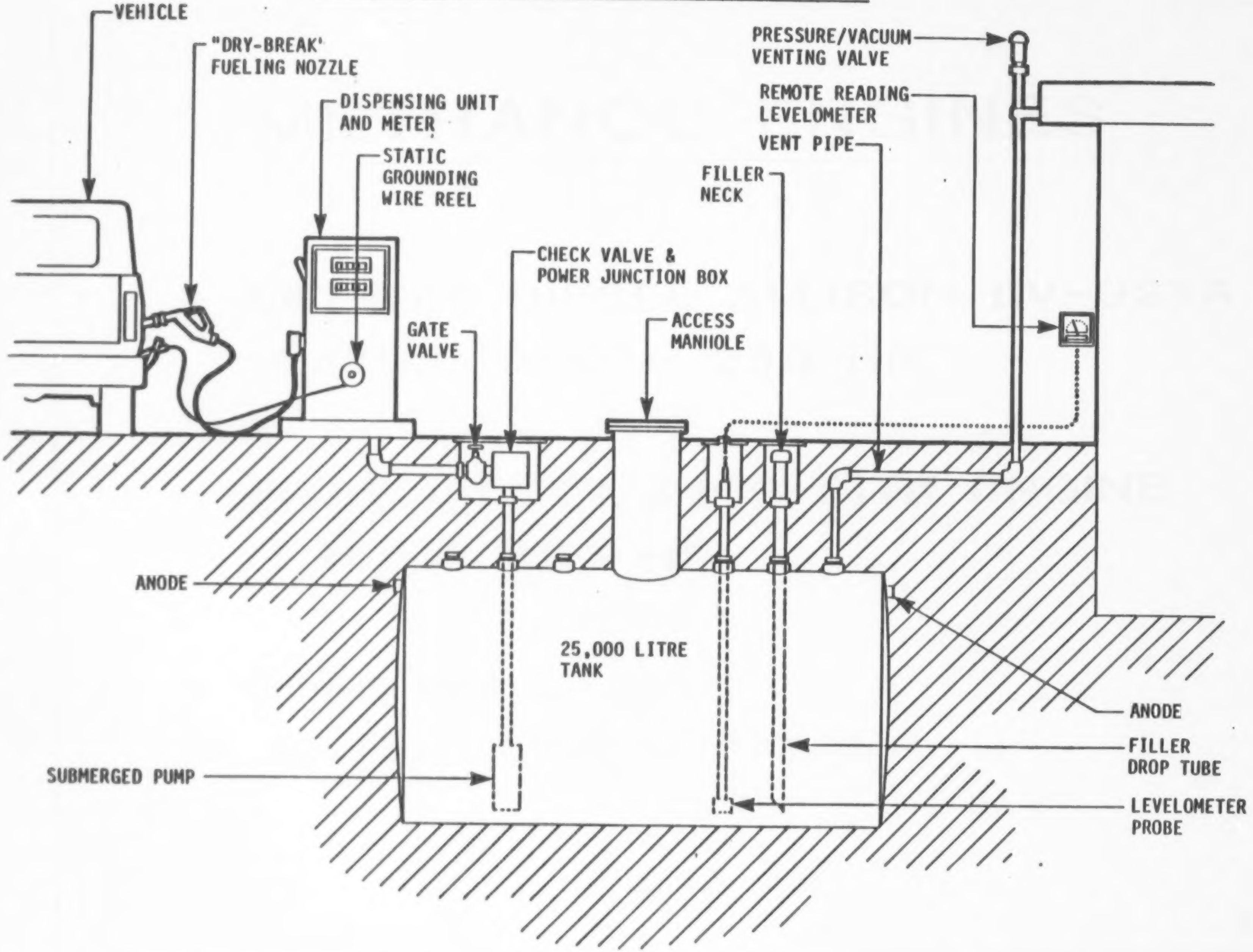
PRECAUTIONS (SPILLS):

- INSTRUCT PERSONNEL IN PROPER CLEAN-UP PROCEDURES
- CONSTRUCT DIKE AROUND FUELLING STATION AREA TO CONTAIN SPILLS. HAVE ABSORBANT MATERIAL NEAR BY
- DILUTE SPILL AREA HEAVILY WITH WATER
- MAKE ARRANGEMENTS FOR PROPER DISPOSAL OF SPILLED MATERIAL.

PRECAUTIONS (EMISSIONS):

- ENSURE PROPER VENTILATION WHEN ENGINES ARE OPERATING
- INVESTIGATE EFFECTIVE MECHANISMS FOR ALDEHYDE CONTROL, E.G. ENGINE MODIFICATIONS, FUEL FORMULATION MODIFICATIONS, EXHAUST CATALYSTS.

FIGURE 1 SCHEMATIC OF METHANOL FUELING INSTALLATION


VEHICLE
"DRY-BREAK" FUELING NOZZLE
DISPENSING UNIT AND METER
STATIC GROUNDING WIRE REEL
GATE VALVE
CHECK VALVE & POWER JUNCTION BOX
ACCESS MANHOLE
FILLER NECK
VENT PIPE
REMOTE READING LEVELOMETER
PRESSURE/VACUUM VENTING VALVE
ANODE
25,000 LITRE TANK
SUBMERGED PUMP
ANODE
FILLER DROP TUBE
LEVELOMETER PROBE

METHANOL ENGINES

- DETROIT DIESEL ALLISON 6V-92TA
  RATING 200 – 250 HP

- CATERPILLAR 3406 DITA ENGINE
  RATING 350 HP

- CUMMINS L-10
  RATING 200 – 250 HP

CONVERSION PROCEDURE

- ENGINE REPLACEMENT
- FUEL SYSTEM CHANGEOUT
- ELECTRICAL & DAS
- MISCELLANEOUS

ENGINE REPLACEMENT

-REMOVE DIESEL POWER-PACK

-POWER-PACK BUILD-UP

-INSTALL METHANOL POWER-PACK

FUEL SYSTEM

-REMOVE PRESENT FUEL TANK

-ISOLATE EXISTING FUEL SYSTEM

-INSTALL METHANOL FUEL
LINES, FILTERS, PUMP & COOLER

-INSTALL METHANOL FUEL TANK

-FLUSH SYSTEM

ELECTRICAL & DAS

-VERIFY VEHICLE ELECTRICAL SYSTEM

-INSTRUMENT WITH DAS

-INSTRUMENT ENGINE CONTROLS, SWITCHES & WARNING SIGNALS

MISCELLANEOUS

-STRUCTURAL

-TUNE AND DEBUG SYSTEM

-DECALS AND PAINTING

-FUTURE: *DRY BREAK FUELING
*ENGINE COMPARTMENT FIRE
EXTINGUISHING

FEDERAL GOVERNMENT POLICIES ON
USE OF ALTERNATIVE TRANSPORTATION FUELS

E. EUGENE ECKLUND
OFFICE OF TRANSPORTATION SYSTEMS
U. S. DEPARTMENT OF ENERGY

PRESENTED TO
DIESEL PARTICULATE CONTROL / ALTERNATIVE FUELS SYMPOSIUM

U. S. ENVIRONMENTAL PROTECTION AGENCY
REGION 5
CHICAGO, ILLINOIS
JANUARY 27-28, 1987

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FEDERAL GOVERNMENT POLICIES ON USE OF ALTERNATIVE TRANSPORTATION FUELS

E. Eugene Ecklund

U.S. Department of Energy

Presented to "Diesel Particulate Control/Alternative
Fuels Symposium" EPA Region 5, Chicago, January 27-28, 1987

Although the federal government has sponsored research and development on producing and using alternative fuels for the total spectrum of applications for well over a decade, there are no policies that specifically address implementation on a broad scale. The discussions today address highway transportation, and the remaining remarks are confined to that segment. Following a very brief introduction as to why alternative fuels are important to our country and the options available in the near term, the material focuses on alcohol fuels and natural gas as having the most meaningful appeal and opportunities. Finally, discussion addresses policy-related actions.

The world will not run out of petroleum for a long time, nor will the United States. However, we do not have to run out to be in trouble. We need only to have world demand strain the availability of supply. History has shown that a difference of +5% in the use/supply differential provides a swing from fuel glut to lines at retail stations or vice versa.

Until 1963, the U.S. provided over half the petroleum ever produced. In 1970, U.S. oil production peaked and it has generally declined since that time. From 1977 through 1985, U.S. discoveries of oil have been only one third the amount produced. U.S. petroleum use has outstripped production since the 1940s. Use by transportation has exceeded domestic production since 1975. All of this has occurred despite drilling 40,000 to 100,000 new wells per year for the past 35 years.

The last truly large petroleum discovery in the U.S. was the North Slope (in 1970) which increased recoverable reserves by about one third. However, the U.S. appetite for oil, even with conservation and fuel switching that occurred following 1973 and 1979, is tremendous, and the present demand of 15 million barrels per day would use up all of the original North Slope crude in two years if it were the only source of supply. More significant at this time is that North Slope oil production is at its peak and will decline appreciably within five years.

In order to offset the shortage of domestic petroleum we rely on imports, and it is improbable that we can change this in the decades ahead. Although imports are lower than in 1979 they are again increasing. In 1986 imports were about 35 percent of consumption. Experts predict that by 1995 imports will reach 50 percentof supply, and rise to 60-70 percent in the decade that follows. In view of the effect of imports on the balance-of-payments, this should be of grave concern. Also, as imports grow so will our reliance on OPEC and Middle East oil. The Middle East has 50 percent of the world"s reserves, and by the year 2000 will produce 50 percent of the world supply. Yet this region is politically unstable and the source of past supply upsets. The point is that we are still vulnerable to foreign supply upsets, and these can be due to either deliberate action or accidental events.

Transportation is almost totally (97 percent) dependent on petroleum. Further, transportation now uses 63 percent of the total oil consumed in this country. Since 1979, other sectors have largely switched from petroleum, whereas (despite small cars) transportation use is increasing. Thus in the event of another shortfall in petroleum supply, transportation will bear the brunt of the shortage. Means to use substitutes would therefore be highly desirable, though not readily accomplished. There are also environmental reasons for use of alternative fuels, but these will be left to others on this program to address.

Technology is not a barrier to the use of alcohols, natural gas, liquid petroleum gases (LPG) or synthetic fuels that resemble gasoline and diesel fuel. Synfuels can serve as a direct substitute for petroleum based fuels, and act in substantially the same manner without any anticipated surprises. LPG, which is made during petroleum refining or stipped from natural gas, has long been used in fleet operations and a million or more vehicles now operate on it. The techniques to use natural gas are much the same as for LPG, except that natural gas is stored as a compressed gas rather than as a liquid as in the case of LPG. Storage of compressed natural gas is bulky, the energy density being about one-sixth that of gasoline, so it takes greater volume to achieve comparable vehicle range. Storage tanks are rugged to withstand gas pressure used to increase the amount stored, thereby increasing fuel system weight and volume. Vehicles with spare space or substantial volume may provide room to accommodate this, making it easier to arrange for use in large vehicles. Alcohols also have lower energy density than petroleum products; ethanol having about two thirds that of gasoline and methanol about half as much (diesel has about 10 percent greater energy density than gasoline). These comparisons have been made to gasoline because LPG, natural gas (or methane) and alcohols are high octane fuels, providing a logical substitution for gasoline. Diesel fuel has low octane number, and high cetane number. Cetane number is the appropriate rating of diesel ignition quality, and fuels with the high cetane rating desirable for diesel use have low octane number, and vice versa. However, means have been found to use these high octane fuels in diesel engines, though engine modifications are generally required. One of the reasons that the use of natural gas diesel fuel. Synfuels can serve as a direct substitute for petroleum based fuels, and act in substantially the same manner without any anticipated surprises. LPG, which is made during petroleum refining or stipped from natural gas, has long been used in fleet operations and a million or more vehicles now operate on it. The techniques to use natural gas are much the same as for LPG, except that natural gas is stored as a compressed gas rather than as a liquid as in the case of LPG. Storage of compressed natural gas is bulky, the energy density being about one-sixth that of gasoline, so it takes greater volume to achieve comparable vehicle range. Storage tanks are rugged to withstand gas pressure used to increase the amount stored, thereby increasing fuel system weight and volume. Vehicles with spare space or substantial volume may provide room to accommodate this, making it easier to arrange for use in large vehicles. Alcohols also have lower energy density than petroleum products: ethanol having about two thirds that of gasoline and methanol about half as much (diesel has about 10 percent greater energy density than gasoline). These comparisons have been made to gasoline because LPG, natural gas (or methane) and alcohols are high octane fuels, providing a logical substitution for gasoline. Diesel fuel has low octane number, and high cetane number. Cetane number is the appropriate rating of diesel ignition quality, and fuels with the high cetane rating desirable for diesel use have low octane number, and vice versa. However, means have been found to use these high octane fuels in diesel engines, though engine modifications are generally required. One of the reasons that the use of natural gas and alcohols in diesels is of interest is that less harmful exhaust emissions are obtained. These lighter fuels result in little, if any, particulates. Unburned methane from natural gas use is photochemically non-reactive. Unburned alcohol fuels also have lower reactivity than petroleum hydrocarbon emissions, and alcohol combustion results in substantially reduced oxides of nitrogen. However, beneficial emissions effects can not be assumed from rudimentary fuel substitution. Appropriate features need to be designed into the system build or modification. Benefits from natural gas use, for example, are usually noted on the basis of engine-out results, and conventional exhaust treatment systems work much better on petroleum combustion products than on those from natural gas. It should be noted that although either ethanol or methanol can be burned, economics for ethanol use are unfavorable, and therefore neat ethanol is seldom considered for use in this country. Utilization technology is similar and transferable between the two alcohols.

Some 25,000 to 30,000 natural gas vehicles are in use in the United States, all but two dozen being of the dual fuel variety. Few of these are diesel conversions. However, so-called spark-assisted diesels operating on natural gas have long been used in stationary applications, and a few truck conversions have been made in the after-market. The number of these is roughly comparable to the number of diesel conversions for use of alcohol. Little attention has been paid to natural gas for diesels by engine manufacturers, but a good many have been involved in alcohol experimentation. There are a variety of options available for modification of alcohol fuels or engines to use alcohols. appreciably more than for natural gas. A technical information and data base is available for all of the techniques, and all have been applied to experimental vehicles. Thus for alcohols, Mercedes and Saab-Scania buses have been operated in Brazil and elsewhere on ethanol plus an advanced cetane improver additive. This additive requires smaller amounts than usual and thus reduces the typically premium cost. Volvo has operated two buses in revenue service for a couple of years that used diesel pilot fuel plus methanol, achieving about an 80 percent diesel fuel replacement. MAN has operated its modified engine with spark ignition in California, Germany and elsewhere. Detroit Diesel Allison has provided its technology for waste heat control and a glow plug in a two-cycle engine as a means to use neat methanol. Other U.S. manufacturers have experimental modified engine designs for use of alcohol. A number of U.S. engine manufacturers are participating in the Canadian government field demonstration program on Methanol in Large Engines (MILE).

The basic role of various federal agencies is defined by their individual missions. The roles of the Environmental Protection Agency (EPA) and the Department of Transportation (DOT) are primarily regulatory, dealing with air quality and safety. DOT, through the Urban Mass Transportation Administrtion (UMTA), also contributes to technology application and to support of local transportation systems.

Since termination of petroleum price control, the role of the Department of Energy (DOE) has been primarily on technology R&D, which had been a major role since establishment. It is the policy of the present administration to reduce industry regulations, and to depend primarily on free market forces to determine change. Present and future activities by federal agencies will reflect these policies.

Although technology is not a barrier to use of methanol and natural gas, there still is much engineering and development required before widespread use of these fuels can be achieved. Under the policies just noted, such activity is considered the province of industry not government. Diesel applications have not progressed as far as those for spark-ignition engines. Initial application efforts concentrated on achieving reasonable engine operation, typically accepting emissions that were produced. Although these results were generally favorable, there has been and continues to be a need for engine optimization including appropriate emissions considerations and trade-offs. This is indicated, for example, by the agreement between General Motors, EPA, New York City and the Center for Auto Safety under which a number of methanol-fueled buses will be supplied to New York City. The agreement includes a substantial amount of research and development by General Motor's Detroit Diesel Allison Division in order to provide a more appropriate product. A large experience database is necessary to prove reliability and durability. R&D activities in progress will contribute substantially to this. However, these development and design related factors suggest that progress and expansion must be carefully addressed to avoid problems related to premature exposure and/or overextended efforts. Activities are still in the development stage, though one manufacturer has expressed the view that production could start in about four years following identification of an appropriate market.

The Federal Government is substantially involved in matters that impact fuel use, including energy, environment and safety. Congressional requirements for air quality and fuel economy have long existed, and although these are generic in nature their history and makeup center on petroleum products. The government has sponsored research, development, demonstration and forums to bring new technology, consideration and discussion to the fore, and has in a number of ways encouraged the possibility of using new fuels. However, as long as petroleum is in good supply and economical little public interest exists. In this environment it is difficult at best for legislative supoort for any action that would require investment of government funds. As earlier noted, the policy of the administration is to rely on free-market forces to institute changes and/or balance. The strategy of the administration is to rely on balance among energy resources. A modest cushion against a petroleum supply upset is provided by the Strategic Petroleum Reserve. In the area of alternative transportation fuels, appreciable effort has been extended to 'level the playing field' for methanol. This includes EPA's proposed requirements for certification of alcohol-fueled vehicles. Still, agencies have not taken any significant action to clarify matters such as energy content of alternative fuels and their relationship to requirements such as corporate average fuel economy (cafe). There are no long-term alternative fuels plans per se, though the options for transportation have been well identified. DOE, EPA and UMTA have all encouraged methanol fuel application in various ways. DOE also recognizes that natural gas is a good fuel and can play a role in the near future in niche applications, which would include bus use. DOE has concentrated on working with industry to assure its readiness to apply available and appropriate technology when the market is ready. EPA works with industry as well, but concentrates on methanol as a means to improved air quality and apparently considers this a means for creating market pull. UMTA has sought understanding of methanol bus field operating factors and answers to problems through selected investigative demonstrations. At the state level, California and New York are tbe only ones that have significant energy programs in the transportation area. California is a strong proponent of methanol. New York has concentrated on natural gas, but now has some activity with methanol. Some members of Congress have considered a more aggressive federal approach through legislation under consideration that would provide incentives for use of specified alternative fuels and some additional demonstrations (which are contrary to administation policy). Concepts for commercial introduction of methanol fuel into the market have been proposed in printed documents by personnel from both EPA and DOE. It is this authors personal view that since a copious number of participants are necessary to achieve success, it is essential that those who would participate must pick up on such ideas and shape them to meet the needs of their organizations. Whereas all of these attitudes are helpful, conditions are such that serious movement toward commercialization is dependent on free market forces that are not visible in the near term.

In summary, there are several potential fuels to use in place of petroleum products, and the more attractive ones, taking into account energy and environment, are natural gas and methanol. Natural gas use best fits niche markets, like buses, while factors related to methanol permit consideration for wide spread highway transportation use. Substantial groundwork has been laid in government and industry for use of methanol. The basic utilization technology has been developed, delineated and applied to experimental vehicles, including diesel buses. Benefits to the environment have been set forth, analyzed and assessed to a considerable degree. Factors affecting application to urban buses have been investigated, and are being considered in greater detail under broader conditions. Engine manufacturers have been addressing methanol designs, and among them have covered a range of strategic options. There are no federal plans to move to alternative fuels, though a great amount of background has been laid and there is probably sufficient information to sort out the options. There has been encouragement for interest and use from federal quarters, particularly for methanol. The government policy is to rely on free market forces, and the public shows little interest in petroleum substitutes during this period of plentiful petroleum. Since it takes appreciable time to design vehicle systems, test, evaluate and prove them, industry technological progress may pace the transition to commercialization. If a market were apparent to the industry, it would take about four years (minimum) to achieve production. To encourage this and to achieve wide spread interest, grass roots support from those in the community that would be served is vital.

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U.S. PETROLEUM PRODUCTION

- OVER HALF OF WORLD's TOTAL UNTIL 1963
- PEAKED IN 1970
- 1977 - 1985 DISCOVERIES EQUAL 1/3 OF PRODUCTION
- USE GREATER THAN PRODUCTION SINCE 1940s.
- TRANSPORTATION USE GREATER THAN PRODUCTION SINCE 1975
- 40,000 - 100,000 WELLS DRILLED PER YEAR FOR 35 YEARS
- NORTH SLOPE (1970) INCREASED RESERVES BY 1/3
- NORTH SLOPE ALONE WOULD LAST 2 YEARS
- NORTH SLOPE PRODUCTION AT PEAK

Slide Presentation..............................E. Eugene Ecklund

FOREIGN OIL RELIANCE

- IMPORTS AT 35% AND INCREASING
- 1995 IMPORTS 50%
- FOLLOWING DECADE IMPORTS 60-70%
- MIDDLE EAST RESERVES 50% OF WORLD'S
- MIDDLE EAST 2000 PRODUCTION 50% OF WORLD'S

TRANSPORTATION RELIANCE ON PETROLEUM

- PETROLEUM MAKES UP 97% OF TRANSPORTATION FUEL
- TRANSPORTATION USES 63% OF U.S. OIL USE
- TRANSPORTATION WILL BEAR BRUNT OF SHORTFALL

AVAILABLE SUBSTITUTES

- SYNTHETIC GASOLINE AND DIESEL FUEL
- LIQUID PETROLEUM GASES (1 MM VEHICLES)
- NATURAL GAS (25,000)
  - FEW DIESELS
- ALCOHOLS
  - ETHANOL COSTLY
  - METHANOL FAVORED
- EMISSIONS IMPROVED WITH NG OR ALCOHOLS
- VARIETY OF ALCOHOL DIESEL TECHNOLOGIES
  - MANUFACTURER INVOLVEMENT
  - SUBSTANTIAL DESIGN DEVELOPMENT
  - PRODUCTION START UP TAKES 4 YEARS

FEDERAL INVOLVEMENT

- IMPACTS ENERGY, ENVIRONMENT AND SAFETY
- SPONSORED R&D, DEMONSTRATIONS AND FORUMS
- FREE-MARKET POLICY
- RELY ON BALANCED ENERGY RESOURCES
- SPR PROVIDES PETROLEUM SUPPLY CUSHION
- ENCOURAGE LEVEL PLAYING FIELD
- NO SPECIFIC LONG-TERM PLANS
- DOE, EPA AND UMTA HAVE ENCOURAGED METHANOL
- NATURAL GAS CAN SERVE NICHES
- SOME STATE DEMONSTRATIONS

SUMMARY

- POTENTIAL FOR USE OF METHANOL AND NATURAL GAS
- SUBSTANTIAL GROUNDWORK LAID FOR MEETHANOL
  - BASIC UTILIZATION TECHNOLOGY
  - BENEFITS TO ENVIRONMENT
  - FACTORS AFFECTING BUS APPLICATIONS
- MANUFACTURERS ADDRESSING METHANOL DESIGNS
- NO FEDERAL PLANS, BUT ENCOURAGEMENT
- PRESENT RELIANCE ON FREE MARKET FORCES
- INDUSTRY PROGRESS MAY PACE USE
- GRASS ROOTS SUPPORT IS VITAL

UMTA

METHANOL PROGRAM PRESENTATION

at the

EPA Diesel Particulate Control
and Alternative Fuels Symposium

given by

Vincent R. DeMarco
Acting Director
Office of Bus & Paratransit Systems
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METHANOL PROGRAM

REASONS FOR CONSIDERING METHANOL

- 1991 EPA particulate matter standards for bus diesel engines are extremely difficult to meet, but can be met with methanol fuel
- Methanol is a relatively clean burning fuel
- Projected long term shortage of diesel fuel
- Projected diesel fuel price makes methanol fuel an attractive alternative
- Methanol fuel can be made from domestic sources of natural gas, coal, and wood

METHANOL PROGRAM

BASIS OF UMTA METHANOL PROGRAM

- Need to provide transit agencies with the data they will need to make a smooth transition to fleet-wide use of methanol

- Need to establish effects of methanol on:
  - Vehicle reliability and maintainability
  - Vehicle driveability
  - Cost of ownership

- Need to determine:
  - Safety procedures in using methanol
  - Overall environmental impact
  - Public health impact
  - User training needs

METHANOL PROGRAM

GOALS AND OBJECTIVES

- Establish methanol as a safe and cost effective fuel for transit buses
- Identify and address the environmental and public health effects of methanol use
- Obtain operational data on methanol use
- Resolve initial operational problems
- Expand the potential conversion market by developing low-cost modification kits

METHANOL PROGRAM

PROGRAM SCOPE

- Multiple revenue service evaluations to collect data on cost, safety and operational experience on:
  - Up to 6 sites (including cold weather)
  - Up to 100 buses total
  - New buses and modified existing buses

- Support studies to analyze safety, environmental, public health, and operational impact issues

- Develop handbook and training modules for transit authorities to use in converting operations to methanol fuel

METHANOL PROGRAM

PROGRAM ELEMENTS

- Bus revenue service demonstrations in:
  - Golden Gate Transit (CA) - 1 GM and 1 MAN
  - Florida DOT - 3 GM (mod 6V71N engines) in Jacksonville (FL), (20 more later)
  - Seattle (WA) - 10 MAN
  - Riverside (CA) - 3 GM (mod 6V92TA engines)
  - New York City (NY) - 6 new GM buses, (26 more later)
  - SCRTD (CA) - 30 (to be selected)
  - Winter site - to be selected

- Related demonstrations in:
  - Berlin, W. Germany - 7 MAN and 7 DB buses
  - Verde Valley (AZ) - 2 gasoline bus mods
  - Baltimore (MD) - vans/taxicabs

METHANOL PROGRAM

PROGRAM ELEMENTS (CONTINUED)

- o Program Support Studies
  - o User training - Battelle
  - o Data collection requirements for UMTA methanol demonstrations - Battelle
  - o Methanol handbook - Argonne
  - o Methanol fuel specifications - Argonne
  - o Environmental Impact Assessment - Argonne
  - o Public health and safety - UMTA/OSHA

- o Related methanol efforts
  - o Emissions testing - EPA
  - o Automobile evaluations - Dept. of Energy
  - o International efforts - Int. Energy Agency

METHANOL PROGRAM

PROGRAM PARTICIPANTS

- Government Agencies
  - U. S. DOT/UMTA
  - U. S. Environmental Protection Agency
  - U. S. Department of Energy
  - Occupational Safety and Health Admin.
  - International Energy Agency

- Methanol Bus Demonstration Sites
  - Golden Gate Transit (FL)
  - Florida Department of Transportation
  - Seattle (WA)
  - Riverside (CA)
  - New York City (NY)
  - Southern California Rapid Transit District
  - Winter demo site - to be determined

- Other
  - APTA Bus Maintenance Committee
  - Battelle Columbus Laboratories
  - Argonne National Laboratory

METHANOL PROGRAM

BUS DEMO IN GOLDEN GATE TRANSIT (CA)

- Number of buses
  - 1 new GM RTS-04; with modified 6V-92TA two-stroke engine; electronic unit injectors, by-pass blower; increased compression ratio; and glow plugs for starting and low-speed, low-load operation. Revenue service began in August 1983.
  - 1 new MAN SU-240; with D-2566 FMUH four-stroke lean burn stratified charge engine; and direct-injection with spark assisted ignition. Revenue service began in July 1984.

- Cost of Demo (includes cost of buses)
  - California Energy Commission - $1.5 million
  - UMTA Section 3(a)(1)(C) - $830,000

- Status
  - Two Methanol Buses are in service

METHANOL PROGRAM

BUS DEMO IN JACKSONVILLE, FL

- Number of buses
  - 3 reengined GM New Looks, with modified 6V71N engines. Revenue service began in June 1986.

- Cost of Demo (excluding cost of buses)
  - Florida DOT - $274,555
  - UMTA Section 6 - $2,343,169 (to develop modified engines and evaluate in-service results). Project began in 12/80 with a
    Phase I - Feasibility Study;
    Phase II - Engine and Bus Conversion; and
    Phase III - Revenue Service Demonstration.

- Status
  - Buses are in service since June 1986

METHANOL PROGRAM

BUS DEMO IN SEATTLE METRO, WA

- Number of buses
  - 10 MAN

- Cost of Demo (including cost of buses)
  - Seattle METRO - $2.0 million; includes cost of buses at $170,000 each, cost of fueling facilities at $150,000, and cost of emissions testing at $100,000.
  - UMTA Section 6 - $200,000 (to document demonstration results)

- Status
  - Bus deliveries have been made; start of service in February 1987

METHANOL PROGRAM

BUS DEMO IN RIVERSIDE, CA

- Number of buses
  - 3 reengined GM coaches, with modified 6V92TA engines

- Cost of Demo (excluding cost of buses)
  - GM - $975,000 to retrofit 3 buses and provide field support for operation of the buses for three years

- Status
  - Buses expected to be in service in July 1987

METHANOL PROGRAM

BUS DEMO IN NEW YORK, NY

- Number of buses
  - 6 new GM RTS coaches, with modified 6V92TA engines

- Cost of Demo (including cost of buses)
  - GM - $5.6 million; includes cost of R&D ($3.6 million), cost of buses ($207,000 each), and cost of providing field support for the buses for three years
  - UMTA Section 6 - $200,000 to document evaluation results

- Status
  - R&D effort is underway; bus deliveries expected in early 1988

METHANOL PROGRAM

BUS DEMO IN SCRTD, LOS ANGELES, CA

- **Number of buses**
  - **30 to be purchased (using UMTA Section 9)**

- **Cost of Demo (less cost of buses), includes emissions laboratory with two transient dynamometers (one engine and one chassis)**
  - **SCRTD - $466,667**
  - **CARB - $1.3 million**
  - **UMTA Section 3(a)(1)(C) - $1.4 million**

- **Status**
  - **Bus procurement in progress; award anticipated in March 1987**
  - **Service should begin in fall 1988**

METHANOL PROGRAM

TECHNICAL SUPPORT - TRAINING MODULE

- Performing Organization: Battelle Lab.

- Basic Training Module Contents
  - Introduction of Basic Properties
  - Fire and Flammability Properties
  - Health and Toxicity Properties
  - Decisions needed by a Local Property
  - Maintenance Personnel Training
  - Driver and Other Personnel Training

- Schedule
  - Identification of Training Requirements - 12/86
  - Develop Initial Training Manual - 5/87
  - Provide Methanol Training - 6/87 to 12/88
  - Provide Final Training Module - 3/89

METHANOL PROGRAM

TECHNICAL SUPPORT - DATA COLLECTION

- Performing Organization: Battelle Lab.

- Basic Data Collection Requirements
  - Capital Cost Impacts
  - Operating and Maintenance Cost Impacts
  - Vehicle Driveability & Performance Impacts
  - Equipment Reliability
  - Vehicle Emissions
  - Environmental Impacts
  - Safety and Health Impacts

- Schedule
  - Identification of Data Collection Requirements - 3/87
  - Develop Initial Data Collection Forms - 6/87
  - Analyze Data Collected by the Demo Sites - 6/87 to 12/88
  - Provide Report on Data Collected - 3/89